HEAT

HEAT

ENGINEERING EDUCATION SERIES

HEAT

PREPARED IN THE

EXTENSION DIVISION OF

THE UNIVERSITY OF WISCONSIN

BY

E. M. SHEALY

ASSISTANT PROFESSOR OF STEAM ENGINEERING

THE UNIVERSITY OF WISCONSIN

FIRST EDITION

McGRAW-HILL BOOK COMPANY, INC.

239 WEST 39TH STREET, NEW YORK

6 BOUVERIE STREET, LONDON, E. C.

1914

THE · MAPLE · PRESS · YORK · PA

PREFACE

A knowledge of the nature and the laws of heat should form the basis for the study and thorough understanding of all heat-using machinery, such as the steam engine, the gas engine, the refrigerating machine, and the air compressor. This text is designed to supply the fundamental knowledge necessary for the successful study and understanding of this class of machinery. This text has also been regarded as a good foundation for advanced studies in these classes of machinery, treated as separate, specialized courses of study.

The first part of the text treats of the fundamental laws relating to the nature, generation, transfer, and transformation of heat, and presents familiar examples of their practical application in all cases. In this part also the expansion and compression of gases, and the nature and properties of steam, ammonia, carbon dioxide, and sulphur dioxide are taken up.

In the last part of the text the principles of the steam engine, the gas engine, the refrigerating machine, and the air compressor are treated, and the relation of the laws of heat to these classes of machinery is shown. No attempt is made to present a complete treatment of these classes of machinery, but enough is given so that one who has had no experience with them may understand the relation of the laws of heat to their principles and their operation.

Our experience has shown that this treatment of the subject of heat is well adapted to the requirements of engineers and firemen who have had some experience with heat-using machinery, and understand its operation, but who feel that they do not know enough about the laws of heat to allow them to take up advanced or special studies of this class of machinery with profit. Moreover, this treatment is broad enough to meet the needs of others who are interested in any of the applications of heat.

The author desires to acknowledge the assistance of Mr. E. B. Norris, Associate Professor of Mechanical Engineering in the Extension Division of The University of Wisconsin, in the preparation of the text and for valuable suggestions and for pains-taking proof-reading and criticism of the manuscript.

E. M. S.

MADISON, WIS.,
March, 1914.

CONTENTS

CHAPTER IV

Transferring and Measuring Heat

CHAPTER V

Generation of Heat

CHAPTER VI

Measurement of Pressure and Effects of Heat on Gases

CHAPTER VII

Laws of Gases

CHAPTER VIII

Compression and Expansion of Gases

CHAPTER IX

Properties of Steam and Other Vapors

CHAPTER X

Condensation and Evaporation

CHAPTER XI

The Steam Engine

CHAPTER XII

Multiple Expansion Engines

CHAPTER XIII

AIR COMPRESSION

CHAPTER XIV

GAS ENGINES

CHAPTER XV

REFRIGERATION

CHAPTER XVI

House Heating

LIST OF TABLES

HEAT

CHAPTER I

TEMPERATURE AND ITS EFFECTS

1. Temperature.—If we touch a body and it feels hot we are accustomed to say that it has a high temperature; likewise, if the body feels cold, we are accustomed to say that its temperature is low. Thus, the sensations experienced upon touching a substance give a general idea of the state of temperature of the substance, and the terms *hot*, *warm*, *tepid*, *chilly*, and *cold* are used to indicate the amount of temperature. These terms, however, give only a general idea of the temperature. If the hand is held in cold water for a while and is then placed quickly in warm water, the warm water will feel much warmer than it actually is. If a small quantity of gasoline which has been in a room until it has attained room temperature is poured on the hand it seems much colder than it actually is. It will be seen from this that the sensations of hot and cold cannot be depended upon in judging temperature and it is therefore necessary to adopt some other means of measuring this quantity where it is desired to obtain more accurate results.

It should be noted that the temperature does not indicate the amount of heat which a substance contains, but indicates only the conditions of the heat in the substance. If one vessel contains a pint of water at a certain temperature and another contains a quart of water at the same temperature, the quart of water has absorbed more heat than the pint has and it, therefore, contains more heat, although its temperature is the same as the pint of water.

2. Thermometers.—A thermometer is an instrument for measuring temperature. The thermometer which is most commonly used consists of a glass tube with a small uniform bore ending in a small bulb at the bottom, the bulb and part of the tube being filled with mercury. The tube is marked in equal divisions, called degrees, which are numbered so the readings may

be referred to by figures. Since mercury expands when heated and contracts when cooled, the height at which the mercury stands in the tube will indicate its temperature. Therefore, when the thermometer is brought into contact with a substance, the mercury soon reaches the same temperature as the substance and will stand at a height in the tube which indicates this temperature.

In making a thermometer, the bulb and part of the tube are filled with mercury, and the tube is then heated to a temperature slightly above the highest for which it is to be used. This causes the mercury to reach a higher point in the tube. The tube is then sealed in a hot flame and allowed to cool, when the mercury will sink in the tube leaving a space above which is not filled with air.

3. Thermometer Scales.—In marking thermometer scales into degrees two fixed points are first marked, namely, the temperature of melting ice, and the temperature of boiling water, in each case the ice and the boiling water being in the open air. On the thermometers which are in common use in the United States, the temperature of melting ice is called 32 degrees (32°) and the temperature of boiling water is called 212 degrees (212°), the space between these two points being divided into 180 equal divisions or degrees (180°). This scale of temperatures is called the *Fahrenheit scale,* and is abbreviated *Fahr.* or simply *F.* On the thermometer which is commonly used in Europe and for physical measurements in America, the temperature of melting ice is marked 0°, and the temperature of boiling water is marked 100°, the space between these two points being divided into 100°. This scale of temperatures is called the *Centigrade scale* and is abbreviated *Cent.* or simply *C.* On each thermometer scale the space above the temperature of boiling water and below the temperature of melting ice is marked off in degrees of the same size as those between these points. Where no temperature scale is mentioned, in this work, the Fahrenheit scale is to be used.

In marking the temperature of melting ice, the thermometer is immersed in a vessel containing cracked ice, as illustrated in Fig. 1, and allowed to remain until the mercury reaches a constant height, and this point is then marked. During this process, the thermometer should be placed low enough in the ice so the mercury is but little above the level of the ice. In making any temperature reading the same precaution should be taken, that is, the

stem of the thermometer should not project very far out of the substance whose temperature is being read. An apparatus for marking a thermometer at the temperature of boiling water, and by which the thermometer may be immersed in the steam arising from the water, is shown in Fig. 2.

It is often necessary to change temperature readings from one scale to the other, and in order to do this the relation between the Fahrenheit and the Centigrade degrees must be known. From

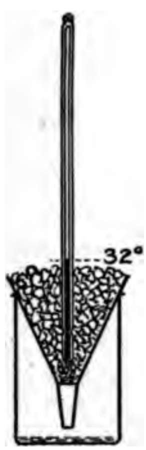

FIG. 1. Testing freezing point on thermometer.

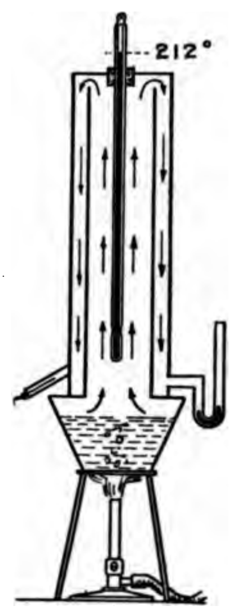

FIG. 2. Testing boiling point on thermometer.

what has been said above it will be seen that 180 Fahrenheit degrees is equal to 100 Centigrade degrees, or the Centigrade degree is $\frac{180}{100}=\frac{9}{5}$ of a Fahrenheit degree and the Fahrenheit degree is $\frac{100}{180}=\frac{5}{9}$ of a Centigrade degree.

Hence to change from Fahrenheit to Centigrade temperature first find how many Fahrenheit degrees the given temperature is above or below the freezing temperature and then multiply by $\frac{5}{9}$. This rule may be expressed by a formula, thus

$$C=(F-32)\tfrac{5}{9}$$

in which C is the temperature on the Centigrade scale and F is the temperature on the Fahrenheit scale.

Examples:

1. The temperature in a certain room is 70° F.; what would a Centigrade thermometer read if placed in the same room?

Solution:

$$\begin{aligned} C &= (F-32)\tfrac{5}{9} \\ &= (70-32)\tfrac{5}{9} \\ &= 38 \times \tfrac{5}{9} = 21.1+° \text{ C.} \end{aligned}$$

2. On a certain winter day a Fahrenheit thermometer reads eighteen degrees below zero (−18° F.); what temperature would a Centigrade thermometer read?

Solution:

$$\begin{aligned} C &= (F-32)\tfrac{5}{9} \\ &= (-18-32)\tfrac{5}{9} \\ &= -50 \times \tfrac{5}{9} = -27.7+° \text{ C.} \end{aligned}$$

In order to change from Centigrade to Fahrenheit temperatures, first multiply by $\frac{9}{5}$ *in order to find how many Fahrenheit degrees the given temperature is above or below the freezing temperature. Knowing how far it is from the freezing point, to find how far it is from* 0° *F. add* 32 *because the Fahrenheit zero is* 32° *below the freezing point.* This may be expressed as a formula thus,

$$F = \tfrac{9}{5}C + 32$$

Examples:

1. It is said that water attains its greatest weight per cubic foot at a temperature of 4° C. To what Fahrenheit temperature does this correspond?

Solution:

$$\begin{aligned} F &= \tfrac{9}{5}C + 32 \\ &= \tfrac{9}{5} \times 4 + 32 \\ &= 7.2 + 32 = 39.2° \text{ F.} \end{aligned}$$

2. A French author states that the temperature of liquid air is −180° C. What is its temperature on the Fahrenheit thermometer?

Solution:

$$\begin{aligned} F &= \tfrac{9}{5}C + 32 \\ F &= \tfrac{9}{5} \times -180 + 32 \\ &= -324 + 32 = -292° \text{ F.} \end{aligned}$$

Fig. 3 shows a Fahrenheit and a Centigrade thermometer placed side by side and illustrates the way in which their scales differ. It will be noticed that their scales read the same at 40° below zero (−40°).

Many people make the mistake of adding or subtracting the number 32 when it is desired to find only *the change in temperature.* For example, some specifications for electrical generators state that the rise in temperature from no load to full load should not exceed 40° C. What rise in temperature would this be in Fahrenheit degrees? Since each degree on the Centigrade scale equals nine-fifths degrees on the Fahrenheit scale, 40 degrees on the Centigrade scale will equal

$$40 \times \frac{9}{5} = 72$$

degrees on the Fahrenheit scale. In this case the fact that the zero points are not the same has no connection with the problem, since we are dealing only with *changes* in temperature and not with readings from the zero points.

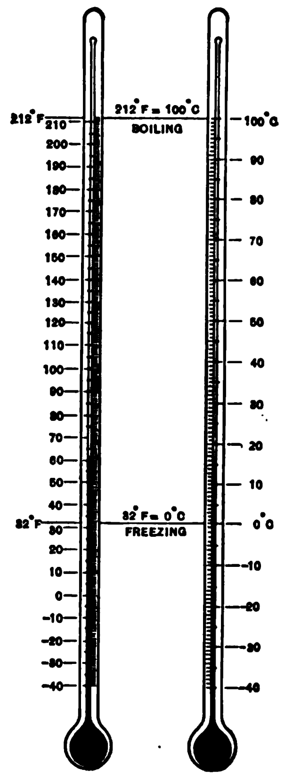

Fig. 3. Comparison of thermometer scales.

Mercury freezes at 39° below zero Fahrenheit (−39° F.) and consequently cannot be used in thermometers which are to be used to measure temperatures below this point. Temperatures lower than this are usually measured with thermometers containing alcohol, since the freezing point of alcohol is −202° F. The alcohol used in thermometers is often colored in order to make it more easily read.

Mercury boils at 680° F. and is, therefore, not suitable for use in thermometers which are used to indicate very high temperatures. As the mercury thermometer is ordinarily made, it should not be used to indicate temperatures higher than about 500° F., but by filling the glass tube above the mercury with an inactive gas, such as nitrogen, under high pressure, the boiling point of the mercury will be raised and a thermometer can be made that may be read up to 900° F. Constructed in this way it forms one of the best instruments for determining stack temperatures in boiler plants.

4. Pyrometers.—Pyrometers are instruments for measuring high temperatures. They are used in some cases to measure temperatures which might be measured by a mercury thermometer but where the mercury thermometer is liable to be broken. They find their greatest use, however, in measuring temperatures which are too high to be recorded on a mercury thermometer.

If two dissimilar metals are welded together and the joint thus made is heated, a current of electricity will be generated, and the strength of the current will be proportional to the temperature of

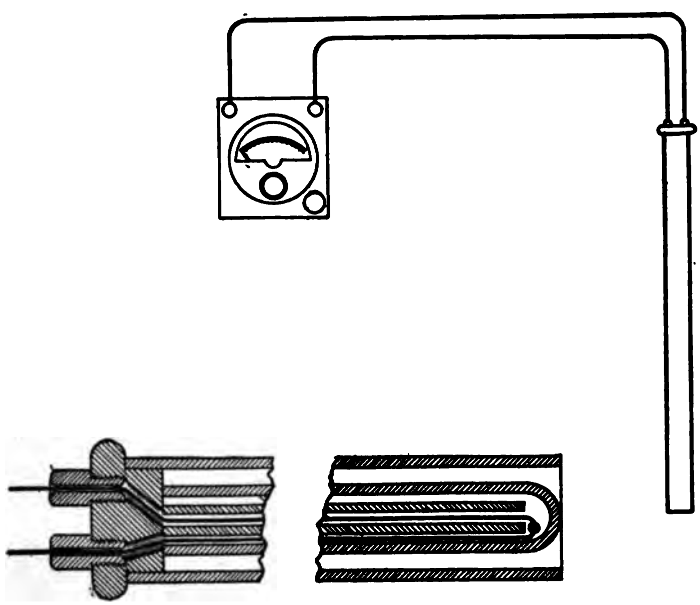

FIG. 4. Le Chatelier electrical pyrometer.

the joint. The current generated in this way may be led away by wires to a galvanometer and there measured. The galvanometer may be marked in degrees and thus made to read the temperature directly. One of the best forms of pyrometers is constructed on this principle. This is known as the *Le Chatelier* pyrometer. The metals used for the joint, or element, as it is called, are platinum and an alloy of platinum and rhodium, both of which are capable of withstanding an exceedingly high temperature. The element is enclosed in a long porcelain tube to protect it

from injury and to render it easier to handle. A Le Chatelier pyrometer constructed in this manner is shown in Fig. 4.

High temperature may be approximately determined by the use of clay cones made for this purpose, as shown in Fig. 5. A series of cones are made of different compositions of clays and have different melting points. The cones are placed at the point where the temperature is to be measured, and the one which barely melts indicates the temperature. These cones are numbered and the melting temperature for each number is furnished by the manufacturer.

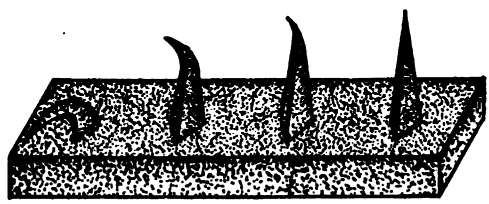

FIG. 5. Clay cone pyrometer.

High temperatures may also be judged approximately by color but the results will depend on the keenness of the eye of the observer and on the degree of illumination under which the observations are made. A piece of steel which would be red hot in a darkened room would be black hot in broad daylight. The following table from Kent's "Handbook for Mechanical Engineers" gives the colors and their corresponding temperatures.

Color	Degrees Fahr.
Incipient red heat	977
Dull red heat	1292
Incipient cherry-red heat	1472
Cherry-red heat	1652
Clear cherry-red heat	1832
Deep orange heat	2021
Clear orange heat	2192
White heat	2372
Bright white heat	2552
Dazzling white heat	2732 to 2912

5. Absolute Temperature.—From the above discussion of temperature scales it will be seen that the zero on the Fahrenheit scale is 32° below the freezing temperature of water and on the Centigrade scale it is at the freezing temperature of water.

Since it is possible to cool substances below the zero points on these two scales it is evident that neither of them represents the true zero of temperature. The true zero would be at such a point that it would be impossible to cool a substance below it. In other words, the true zero would represent an entire absence of heat. While this point has never been reached in cooling substances, experiments indicate that it is 460° below the zero on the Fahrenheit scale.

The temperature −460° is called the *absolute zero* and temperature reckoned from it is called *absolute temperature.* On the absolute scale of temperatures, the size of the degrees is the same as those on the ordinary thermometer, but the number of degrees is counted from −460° F. *Therefore, in order to change from Fahrenheit temperature to absolute temperature, add* 460 *to the number of Fahrenheit degrees;* conversely, *to change from absolute temperature to Fahrenheit subtract* 460 *from the number of absolute degrees.*

Examples:

1. What are the absolute temperatures corresponding to 60° F. and to −30° F.?

Solution:

60° F. corresponds to $460+60=520°$ absolute

−30° F. corresponds to $460+(-30)=430°$ absolute.

2. What are the Fahrenheit temperatures corresponding to 740° absolute and to 320° absolute?

Solution:

740° absolute corresponds to $740-460=280°$ F.

320° absolute corresponds to $320-460=-140°$ F.

6. Expansion of Solids.—Nearly all substances expand when heated and contract when cooled. The amount of this expansion and contraction is greatest with gases and least with solids, but

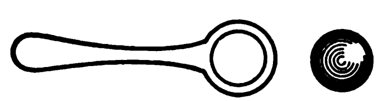

FIG. 6.

even with solids it is great enough to be considered an important factor in nearly all engineering work. The expansion in a substance takes place in all directions if free to do so. Thus if the steel ball shown in Fig. 6 is made just small enough to pass through the ring, it will not do so after being heated. The ball is spherical both before heating and after, showing that it has expanded in all

directions. Although substances expand in all directions when heated, the change in length or linear expansion is of most importance when considering solids, and is the only expansion which is usually considered.

Examples of provision for linear expansion in solids are very common. Steel bridges are often built with one end resting on

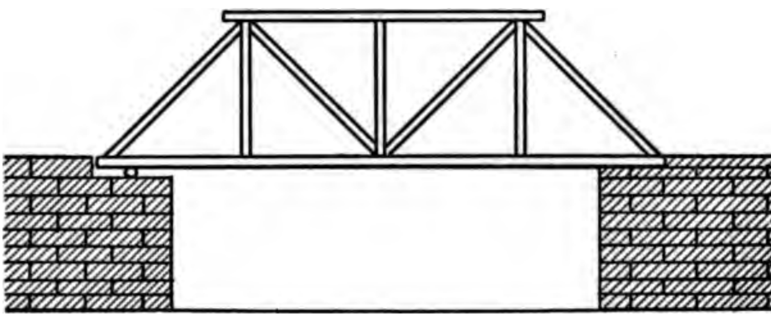

FIG. 7. Bridge set on roller.

rollers as shown in Fig. 7, while the other end is fastened rigidly to the foundation, thus leaving the bridge free to move as it expands or contracts. Provision must be made for expansion in long steam-pipe lines, which are cold when erected. One method of doing this is by inserting an expansion joint in the pipe line, the

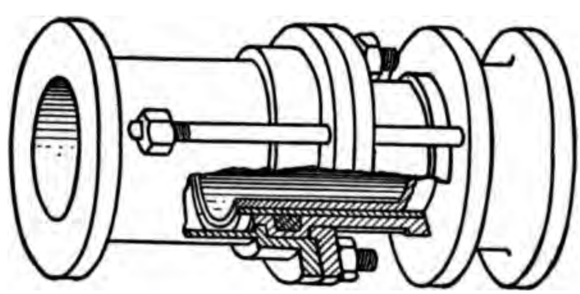

FIG. 8. Slip expansion joint.

expansion joint being constructed so that one part can move with respect to the other, as shown in Fig. 8.

Nickel steel containing 36 per cent. of nickel neither expands nor contracts upon being heated. This metal is sometimes called "invar" and is useful in making steel tapes and other instruments in which expansion would affect their accuracy.

The amount which a solid expands depends upon the range of temperature through which it is heated, the expansion in a particular material being constant for each degree rise in temperature, but differing in different materials. The part of its original length which a solid expands when heated one degree is called its *Coefficient of Linear Expansion.* The coefficients for different materials have been determined for our use by careful experiments and can be found in handbooks or tables under the head of "Coefficients of Linear Expansion." A few of the most common are given here:

COEFFICIENTS OF LINEAR EXPANSION

(Per degree Fahrenheit)

Aluminum	.000012880
Brass, cast	.000010420
Brass, wire	.000010720
Bronze, (3 copper + 1 tin)	.000010270
Carbon, diamond	.000000656
Carbon, gas carbon	.000003000
Carbon, graphite	.000004375
Cast iron	.000005560
Copper	.000009330
Ebonite	.000046800
German silver	.000010200
Glass	.000004980
Gold	.000008030
Gutta percha	.000110200
Ice	.000028400
Lead	.000016390
Marble	.000006510
Nickel	.000007110
Paraffin	.000072250
Platinum	.00C005000
Porcelain	.000002300
Rock salt	.000022470
Silver	.000010700
Solder (1 lead and 1 tin)	.000013950
Steel (untempered)	.000006500
Tin	.000012400
Wood, pine, parallel to fibers	.000003010
Wood, pine across the fibers	.000018950
Wrought iron	.000006480
Zinc	.000016210

The above values are based on a temperature rise of 1° F. For

one Centigrade degree the coefficients would be $\frac{9}{5}$ of those given in the table.

The increase in length of a body due to expansion may be calculated by the following formula

$$e = tCL$$

in which

e = the *change* in length
t = the *change* in temperature
C = the coefficient of linear expansion
L = the original length of the body.

The same formula applies to contraction when a body cools. It should be remembered that if L, the original length, is in feet, e, the change in length, will also be in feet, or if L is in inches, e will also be in inches.

Example:

A steel steam-pipe line is 300 feet long when it is erected, the temperature being 65° F. What will be its length after steam having a temperature of 340° F. is turned into it?

Solution:

The length of the pipe line is 300 feet or $300 \times 12 = 3600$ in. The *change* in temperature is $340° - 65° = 275°$. The coefficient of expansion of steel is, from the table above, .0000065; therefore, the *change* in length of the pipe line will be

$$\begin{aligned} e &= tCL \\ &= 275 \times .0000065 \times 3600 \\ &= 6.435 \text{ in.} = .536 \text{ ft.} \end{aligned}$$

Length of pipe after steam is turned into it $= 300 + .536 = 300.536$ ft.

If two straight strips of different metal are placed side by side and riveted together as shown in Fig. 9, and the double strip thus

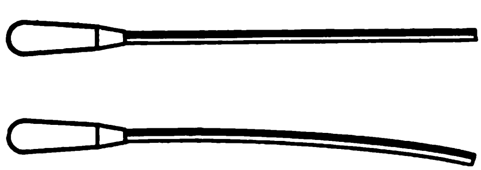

FIG. 9.

made is heated in a gas jet, it will no longer be straight but will bend. The reason for this is that different metals expand different amounts for the same change in temperature. This is shown by the table of coefficients of expansion given above where

it is shown that different substances have different coefficients or rates of expansion. For example, a copper wire 100 ft. long which is subjected to a change of temperature of 80° F. will expand or contract

$$e = 80 \times .000009330 \times 100 \times 12 = .8955 \text{ inches,}$$

and under the same conditions an aluminum wire will expand or contract

$$e = 80 \times .000012880 \times 100 \times 12 = 1.258 \text{ inches, or about 14 per cent. more.}$$

The fact that different metals expand different amounts for the same change in temperature is made use of in the construction of a common form of pyrometer. In this pyrometer, which is illustrated in Fig. 10, a brass rod is enclosed in an iron tube, one end of the brass rod being fastened to the corresponding end of the iron tube, the other ends being independent of each other. A dial and case are fastened to the free end of the iron tube and a pointer connected to the brass rod by a mechanism which allows the pointer to move over the dial when the rod moves with respect to the tube. When the pyrometer is subjected to a high temperature, as when placed in a chimney through which hot furnace gases are passing, the brass rod expands more than the iron tube although both are at the same temperature, and the pointer moves over the dial, which is marked in degrees, and takes up a position which corresponds to the temperature of the rod and tube.

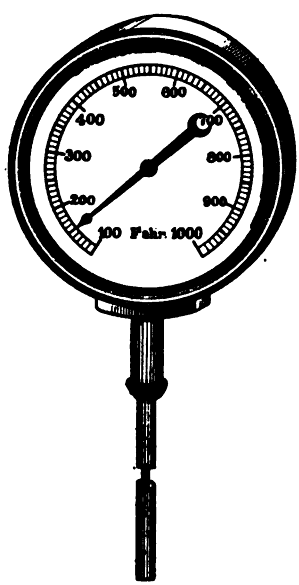

FIG. 10. Iron tube pyrometer.

When these pyrometers are first subjected to a high temperature, the pointer will move backward for a time and will then stop and move forward. This is because the iron tube is affected by the heat first since it is on the outside, and hence it expands faster than the brass rod. As soon as the heat penetrates to the

inside of the tube and reaches the rod it begins to expand also, causing the pointer to reverse its motion. When the tube and rod have reached a uniform temperature the pointer will reach its proper position on the dial.

Another application of the unequal expansion of metals is found in the balance wheel of some watches. Temperature affects the balance wheel and hair spring of a watch, expanding them when the temperature increases and contracting them when the temperature decreases. When they are expanded the spring is weakened and the radius of the wheel is increased, which places the weights further from the center. Both of these effects cause the watch to run slow. These effects may be counteracted by bringing the weight of the wheel nearer the center as the temperature increases, which is done by dividing the rim into segments, as shown in Fig. 11, and constructing the rim of two metals which have different coefficients of expansion, the one having the larger coefficient being placed on the outside. Brass and steel are used for this purpose, the outside of the rim being made of brass and the inside of steel. The ends of the segments are then pulled in by a rise in temperature thus changing the position of the weights enough to counteract the tendency to run slow.

FIG. 11.

7. Stress Due to Expansion.—If the ends of a piece of metal are held rigidly so it cannot expand or contract, a change in temperature will cause a stress in the metal sufficient to lengthen or shorten it the same amount it would have lengthened or shortened if free to move. The stress in metal produced by preventing expansion or contraction may be calculated by the following formula, provided the metal is not stretched to the point where it takes a permanent "set":

$$P = CtE$$

in which

P = stress in metal in pounds per sq. in.
C = coefficient of linear expansion
t = change in temperature
E = coefficient of elasticity of the metal

The coefficient of elasticity, or, as it is sometimes called, the modulus of elasticity, is the load per unit of area divided by the

extension per unit of length. The coefficients of elasticity of some of the common substances are given in the following table:

COEFFICIENTS OF ELASTICITY

Brass, cast	9,170,000
Brass, wire	14,230,000
Copper	16,500,000
Lead	1,000,000
Tin, cast	4,600,000
Iron, cast	15,000,000
Iron, wrought	25,000,000
Steel	30,000,000
Wood	2,000,000

Example:

A street car track has welded joints in the rails which are laid when the temperature is 80° F. What will be the stress in the rails on a winter day when the temperature is 10° F. below zero?

Solution:

The change in temperature to which the rails are subjected is $80-(-10)=90°$. The coefficient of linear expansion of steel is .0000065 and its coefficient of elasticity is 30,000,000:

$$
\begin{aligned}
P &= CtE \\
&= .0000065 \times 90 \times 30{,}000{,}000 \\
&= 17550 \text{ lb. per sq. in.}
\end{aligned}
$$

As this is a safe load for steel, there would be no danger of the rails breaking.

8. Expansion of Liquids.—When a liquid is heated it expands and when it is cooled it contracts. This may be proved by a simple experiment illustrated in Fig. 12 in which a glass flask is filled with water, and is fitted with a stopper through which there is a glass tube with a small bore. When the stopper is placed in the flask the water will rise to a certain height in the tube. If now the flask is heated by a gas jet, the water will rise in the tube, and if the flask is cooled the water in the tube will sink.

Expansion of a liquid by heating causes it to weigh less per cubic foot. That is, heating a liquid decreases its density; and cooling it increases its density. If a glass tube shaped as shown in Fig. 13 is filled with water and a gas jet applied to one branch of it, the water will circulate through the tube in the direction indicated by the arrows. The reason for this is that the water in the branch which is heated becomes less dense, or lighter, which causes it to rise and allows the cooler water in the other branch to flow in and take its place. It is by this means that heating a

liquid causes a *circulation* in it. An application of this principle is found in the hot-water system of heating houses. In this system of heating the pipes, radiators, and boiler are filled with water

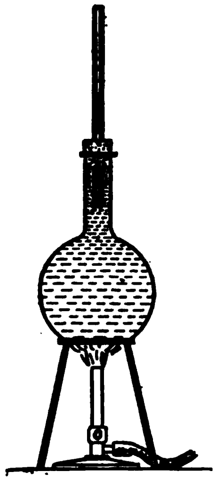

FIG. 12.

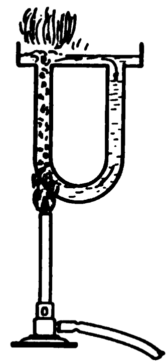

FIG. 13.

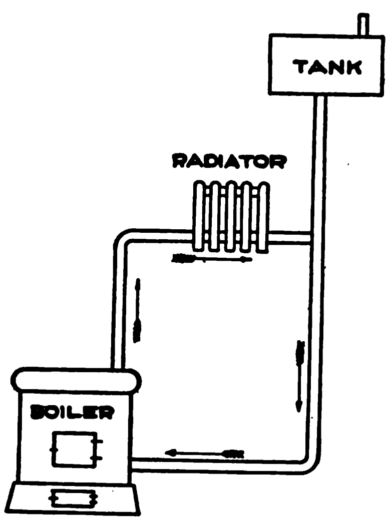

FIG. 14. Hot water heating system.

as shown in Fig. 14. The heat that is applied to the water in the boiler causes it to expand and rise through the flow pipes while an equal volume of cooler water flows into the boiler from the returns

to take the place of the hot water, thus causing a circulation through the entire system.

The following table giving the weight of a cubic foot of water at various temperatures shows how the density of water varies with the temperature:

Temperature of water, degrees Fahr.	Weight of a cubic foot	Temperature of water, degrees Fahr.	Weight of a cubic foot
32	62.40	120	61.71
39	62.42	140	61.38
50	62.41	160	60.99
70	62.3	180	60.57
90	62.11	200	60.12
100	61.99	210	59.88

From the values in this table, the curve shown in Fig. 15 has been plotted to show graphically the variation in the density of water at different temperatures.

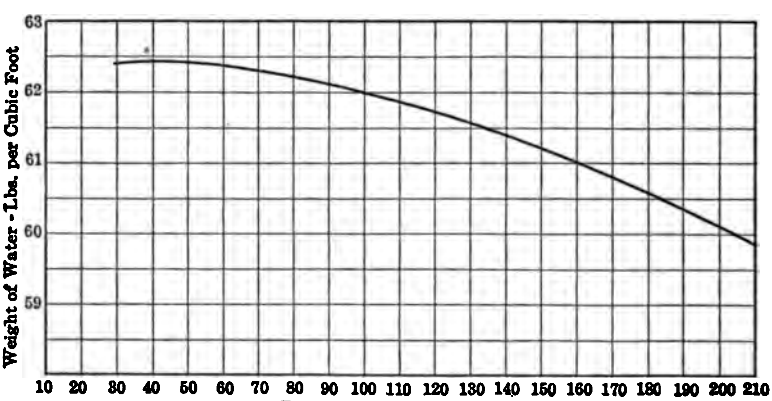

FIG. 15.

Knowing the density of water at different temperatures, the force or pressure causing circulation may be calculated. As an illustration of this, consider the circuit of the hot-water heating system shown in Fig. 14, in which the height of the top radiator above the boiler is 30 ft. Suppose the temperature of the water in the flow side of the circuit is 190° F., and that in the return side is 160° F. The pressure per square foot at the bottom of a column

of water is equal to the height of the column multiplied by the weight of one cubic foot of the water in the column, or

$$P = hw$$

in which

P = pressure at bottom of column in lb. per sq. ft.
h = height of column in feet
w = weight of 1 cu. ft. of the water in the column in pounds.

In this case the weight of a cubic foot of water at 190° F. is, from the curve, 60.35 pounds and the pressure at the base of a column of water 30 ft. high and at 190° F. will therefore be

$$\begin{aligned} P &= h \times w \\ &= 30 \times 60.35 \\ &= 18.105 \text{ lb. per sq. ft.} \end{aligned}$$

The weight of a cubic foot of water at 160° F. is, from the curve, 60.99 pounds, and the pressure at the base of a column of water 30 ft. high and at 160° F. is

$$\begin{aligned} P &= h \times w \\ &= 30 \times 60.99 \\ &= 18.297 \text{ lb. per sq. ft.} \end{aligned}$$

Therefore the difference in pressure between these two columns which causes circulation is

$$18.297 - 18.105 = .192 \text{ lb. per sq. ft.}$$

or

$$\frac{.192}{144} = .001335 \text{ lb. per sq. in.}$$

Different liquids expand different amounts for the same change in temperature, just as solids do, and the rate of expansion is not constant with some liquids. Thus the coefficient of expansion of alcohol is .000722 if taken between 32° and 110° F., and it is only .000611 if taken between 32° and 50° F. The coefficient of mercury, however, is constant through a wide range of temperature, which makes it particularly suitable for use in a thermometer.

In a mercury thermometer the expansion of the mercury is used to measure the temperature. Since mercury has a constant coefficient of expansion, the degrees of temperature will be represented by equal lengths on the stem of the thermometer.

In general, liquids are less dense when warm than when cold,

but water behaves somewhat differently, reaching its greatest density at a temperature of 39° F. At temperatures either above or below 39° F. water is less dense than it is at 39°. A direct and important result of this is that ice forms on the surface of water instead of at the bottom, and hence helps to prevent rivers and lakes from freezing solid.

The cooling of a body of water takes place at the surface. As soon as the surface water is cooled it sinks to the bottom and warmer water rises to the surface to take its place, and this action continues until the entire body of water has reached a temperature of 39° F., at which the water reaches its maximum density. If the surface water is cooled to a lower temperature it remains at the surface since it is lighter than the water at the bottom, which is at 39°. Hence, when the temperature of the surface water has fallen to 32° it freezes, and the ice is formed at the surface. Moreover, the water expands considerably in freezing, hence the ice will float, since it occupies more volume than the water from which it was formed. Since the water at the top is coldest and the sheet of ice protects that at the bottom, the bottom water will never be colder than 39° unless the water is so shallow as to freeze solid. The fact that the water at the bottom of a lake or river is never colder than 39° F. is of importance in preserving the life of fish.

QUESTIONS

1. The lowest temperature that scientists have been able to produce is −260° C. What temperature is this on the Fahrenheit thermometer? To what absolute temperature does this correspond?

2. Explain why pouring hot water on the neck of a bottle will loosen a glass stopper.

3. Why do the fever thermometers used by physicians have a long cylindrical bulb instead of a spherical one of the same diameter?

4. Expansion joints such as that illustrated in Fig. 8 are usually placed every 150 feet in steam-pipe lines. If the steam carried in the pipe has a temperature of 380° F., and the pipe is erected when the temperature is 0° F., how much traverse or slip should the expansion joint have in order to prevent its pulling apart when steam is turned on?

5. Steel street-car rails will safely stand a pull of 25,000 lb. per sq. in. before taking a permanent "set." If a track is welded on a day when the temperature is 104° F. how cold must the weather be before there is danger of the rails being stressed beyond this point?

6. It is necessary that incandescent electric light globes be sealed air tight. Knowing this, explain from an inspection of the Table of Cœfficients

of Linear Expansion why the wires leading into the globe are made of platinum.

7. In measuring the temperature in the chimney of a power plant, only a Centigrade thermometer was available and this registered 271° C. What was the temperature in the chimney Fahrenheit scale? What is the absolute temperature in the chimney?

8. Why do automobile owners put alcohol in their radiators in the winter?

9. A locomotive wheel 60 inches in diameter is to have a steel tire shrunk upon it. The shop temperature is 68° F. and the tire is to be heated to a dull red color (1,292° F.). To what diameter must the inside of the tire be turned in order to have a diameter, when heated, of 60.48 inches?

10. Why is a mercury thermometer more accurate than an alcohol one?

CHAPTER II

WORK AND POWER

9. Force.—If a weight of one pound is held in the outstretched hand we feel something pulling downward on the hand. This something which is pulling downward on the hand is called *force*, and in this case it is produced by the attraction of the earth upon the weight resting in the hand. The force which the earth exerts is called the force of gravity. In order to prevent the weight from falling it is necessary to exert an equal resisting force in an opposite direction. If the weight held in the hand is increased to 2 pounds, the downward pull upon the hand becomes twice as great, and, in all cases, it is proportional to the weight.

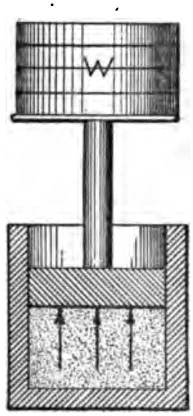

FIG. 16.

Force is produced not only by weights, but also when anything exerts a pull or a push upon another thing. Thus, if any kind of gas under pressure is confined in a cylinder, as shown in Fig. 16, it will exert a force upon the piston in the direction indicated by the arrows, and the piston will move unless prevented from doing so by some external force, such as the weights, W, resting on the piston, which forms a resisting force.

It will be seen that, in both of the cases mentioned above, the effect of the force is to cause motion or to tend to cause it. *We may define force, then, as that which causes or tends to cause motion.* Motion will occur when the force is greater than the resistance, but when the force and resistance are equal they balance each other, and no motion occurs.

10. Work.—When the point at which a force is applied is moved by the force, work is performed. No work will be done in simply overcoming or exerting a force, because it requires only a force to overcome a force, but if the force is overcome through a distance, work is performed. Thus, in the case mentioned above,

in which a weight was held in the hand, no work was done, but only a force exerted to prevent the weight from falling. However, if the weight is *lifted*, work is performed upon it, because the point of application of the force has been moved in a direction opposite to the resisting force. If the weight is lowered, work is also performed, but in this case the weight is doing work upon the hand, since the weight is moved *against* the force applied by the hand.

It will be noticed that *two* things are necessary for work to be performed: first, there must be a *force*, and second, there must be motion. Neither of these things is alone sufficient to produce work, but *both* are necessary.

The unit by which force is measured is the *pound*, and the unit of measure for distance is the *foot*. Since work is a combination of the two quantities, force and distance, its unit is the *foot-pound*.

When a force or resistance of one pound is applied through a distance of one foot, the work performed is one foot-pound. If a weight of one pound is lifted through a distance of 4 feet, the work performed is 4 foot-pounds, or, if a weight of 4 pounds is lifted through a distance of one foot, the work performed is 4 foot-pounds, and in all cases the work performed is equal to the product of the force and the distance through which it is moved, or expressed as a formula:

$$W = FS$$

in which

W = work done, expressed in foot-pounds
F = force or resistance, expressed in pounds, and
S = distance through which the force is overcome, expressed in feet

Examples:

1. A certain hoisting engine lifts a weight of 1500 pounds through a height of 60 feet, how much work is done upon the weight?

Solution:

$$W = FS$$
$$W = 1500 \times 60 = 90{,}000 \text{ foot-pounds.}$$

2. How much work is done on the piston of a steam pump during a single stroke, if the diameter of the piston is 8 inches, the length of the stroke 10 inches, and the steam pressure is 90 lb. per sq. in.?

Solution:

The area of the piston is

$$\text{Area} = .7854\ d^2 = .7854 \times 8^2$$
$$= .7854 \times 64 = 50.2 \text{ sq. in.}$$

The total pressure on the piston is

$$50.2 \times 90 = 4518 \text{ pounds.}$$

The distance through which this force is overcome is 10 inches or $\frac{10}{12} =$ 0.834 feet.

The work done on the piston during a single stroke will be

$$W = FS$$

$$W = 4518 \times .834 = 3768 \text{ foot-pounds.}$$

11. Power.—Power is the rate of performing work. It requires more power to perform a certain amount of work in a short time than in a longer time. Thus, if a derrick lifts a stone weighing 1000 pounds through a height of 20 feet, and the stone is lifted in 2 minutes, a certain power is required; but if the same weight is lifted through the same height in 4 minutes, only one-half as much power is required, although the same amount of work is performed in both cases.

In discussing work it will be noticed that no mention was made of time. When a certain force is applied through a certain distance, the work performed will be the same whether it is performed in a long or short time. The element of time enters into calculations relating to power, because power is the rate of performing work.

The unit of power used in engineering work is the horse-power, abbreviated, H. P., and it is 33,000 foot-pounds of work performed in one minute; and 33,000 foot-pounds per minute is the same as $\frac{33,000}{60} = 550$ foot-pounds of work performed in one second.

Example:

How much power is required to pump 8000 pounds of water per minute to the top of a 7 story building, a height of 75 feet above the pump?

Solution:

The work performed each minute is:

$$W = FS$$

$$= 8,000 \times 75 = 600,000 \text{ foot-pounds}$$

$$\text{Horse-power} = \frac{600,000}{33,000} = 18.18 \text{ H. P.}$$

The sizes of steam, gas, and other engines are designated or rated in terms of horse-power. Thus a 200 horse-power engine is one which can develop power at the rate of 200 H. P. or perform work at the rate of $200 \times 33,000$ foot-pounds per minute.

12. Work Diagram.—Quantity of work may be represented by the area of a figure so drawn that one side represents pressure and the other side represents distance. The area of any figure may be found by multiplying together its height and its length. If the height and length are given in inches, their product will be expressed in square inches. In Fig. 17 suppose the height OA of the figure $OABC$ is 2 inches and its length OC is 4 inches, then the area of the figure is $2 \times 4 = 8$ square inches.

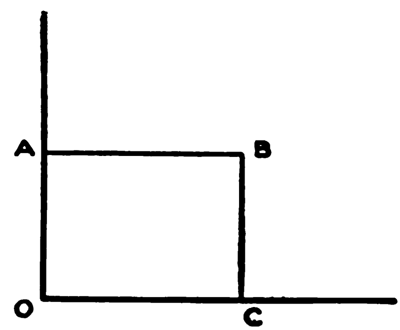

FIG. 17.

If the side OA of the above figure were drawn to represent 2 pounds instead of 2 inches, and, if the side OC were drawn to represent 4 feet instead of 4 inches, then the area would represent $2 \times 4 = 8$ foot-pounds instead of 8 square inches. From this it will be seen that since work is the product of force and distance, any diagram which is drawn with one side representing a force or pressure and the other side representing a distance, will represent by its area the work done.

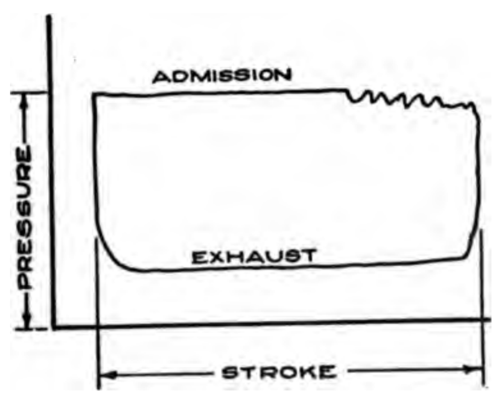

FIG. 18. Work diagram from steam pump.

Fig. 18 shows a work diagram for the steam cylinder of a pump. The height of this diagram represents the steam pressure acting upon the piston and the length of the diagram represents the length of stroke or the distance through which the force due to

the steam pressure moves. Its area, therefore, represents the work performed by the steam upon the piston. This diagram shows that the steam pressure in the cylinder of the pump remains practically constant throughout the stroke. The valve which admits steam opens wide at the beginning of the stroke and remains open until the end of the stroke, when it closes quickly. As soon as the admission valve closes, the exhaust valve opens and the steam pressure in the cylinder immediately falls. The bottom line of the diagram represents the back pressure of the exhaust which acts upon the piston during its return.

Since the above diagram is approximately a rectangle, its area may be calculated by multiplying together its height and its length. If it is desired to express this area in foot-pounds of work, the scale to which the diagram is drawn, and also the proper units, must be considered. Thus, suppose the diagram is drawn to such scale that its height (the distance between the admission and exhaust lines) represents a steam pressure of 80 lb. per sq. in. or $80 \times 144 = 11{,}520$ lb. per sq. ft., and its length represents a stroke of 8 in. or $\frac{8}{12} = \frac{2}{3}$ ft. Then, if the diameter of the piston is 6 in. (equals .5 ft.) the area of the piston is

$$.7854\ d^2 = .7854 \times .5^2 = .196 \text{ sq. ft.}$$

The total uniform pressure acting upon the piston is

$$11{,}520 \times .196 = 2258 \text{ pounds}$$

and as this force of 2258 pounds is moved through a distance of $\frac{2}{3}$ ft. during each forward and return stroke, the work performed is $2258 \times \frac{2}{3} = 1505$ ft. lb. This amount of work is performed in one end of the cylinder. Should the pump be double-acting, that is, taking steam on one side of the piston during one stroke and on the other side of the piston during the return stroke, and if an equal amount of work is performed on each side of the piston, then the total work performed in the cylinder during a forward and return stroke would be $2 \times 1505 = 3010$ ft. lb. If this pump makes 50 double (forward and return) strokes in a minute, the work performed each minute will be:

$$3010 \times 50 = 150{,}500 \text{ ft. lb.}$$

and the horse-power developed will be

$$\frac{150{,}500}{33{,}000} = 4.56 \text{ H. P.}$$

13. The Steam Engine.—One of the common sources of power is the steam engine, a simple form of which is shown in Fig. 19. A steam engine consists of certain stationary parts and certain moving parts. The stationary parts are the frame 2 with the main bearings 29 and 29, the cylinder 3, and the valve chest 23. The moving parts of the engine are the piston 6, the piston rod 30, the crosshead 8, the connecting rod 10, the cranks 12 and 12, the shaft 31, the flywheel 13, the valve 19, the valve rod 18, the eccentric rod 16, and the eccentric 14. The object of the crank, connecting rod, crosshead and piston rod is to change the backward and forward or reciprocating motion of the piston into the rotary motion of the shaft. The reciprocating motion of the piston is transmitted through the piston rod to the crosshead, which is forced to move in a straight line by the guides 9 and 9. One end of the connecting rod is pivoted to the crosshead, which has a reciprocating motion, and the other end is pivoted to the crank and has a rotary motion, since the crank can move only in a circular path. The object of the eccentric, eccentric rod, and valve rod is to change the rotary motion of the shaft into a reciprocating motion at the valve and thus cause the valve to move backward and forward.

The end of the cylinder nearest the crank is called the *crank* end, and the end farthest from the crank is called the *head* end. When the piston moves from the head end to the crank end it is said to make its forward stroke, and when it moves from the crank end to the head end it is said to make its return stroke.

The operation of the steam engine is as follows: High pressure steam is brought to the steam chest by a pipe which enters the steam chest at 27 and the steam fills all the space in the valve chest around the valve. Consider the piston as being at the head end of the cylinder. The eccentric is adjusted at such a position that the valve will admit steam to the head end of the cylinder through the ports or passages 20 and 21, when the piston is at the beginning of its stroke. The pressure of the steam acts upon the piston and pushes it toward the crank end, causing the shaft and fly-wheel to turn. The valve is adjusted to close the port between the steam chest and the head end of the cylinder when the piston reaches some point before the end of its stroke. The point of the stroke at which the admission of steam to the cylinder is stopped is called the point of "cut-off" or simply "cut-off," and the point at which steam is admitted is called the "point of

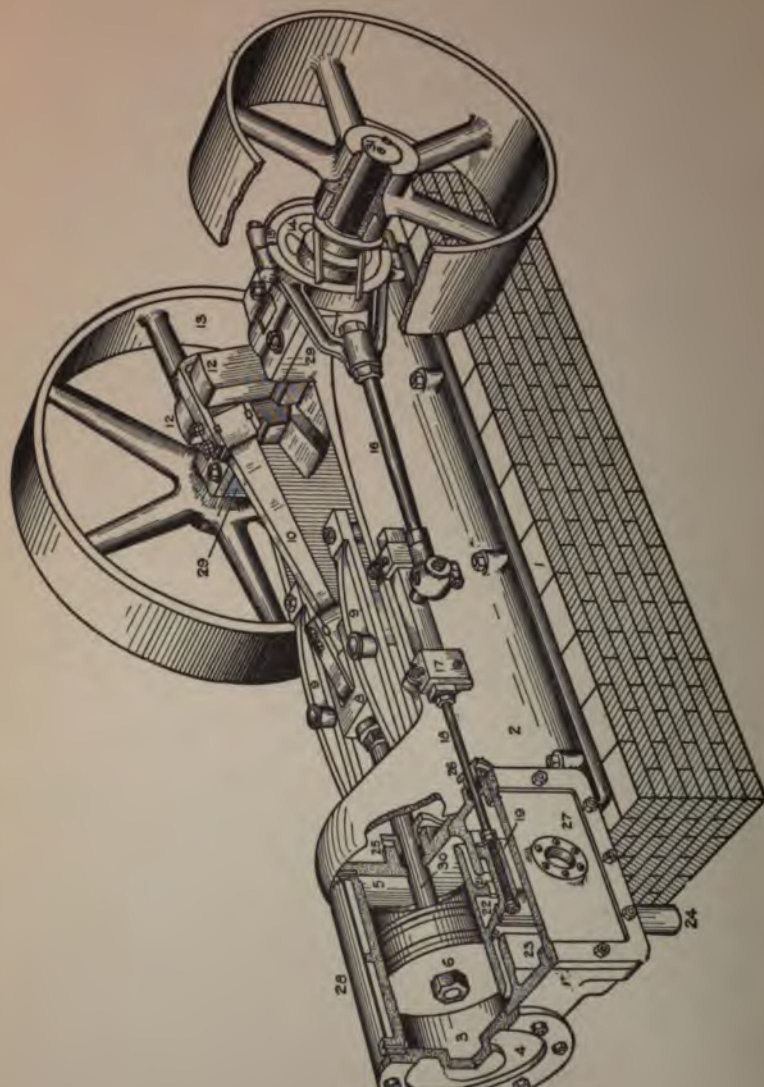

FIG. 19.

admission," or simply "admission." After cut-off, the piston continues to move forward on its stroke, the valve remains closed, and the steam that has been admitted to the cylinder expands and exerts a diminishing pressure upon the piston. When the piston has reached the end of its forward stroke, the valve has moved to such a position that communication is opened between the head end of the cylinder and the exhaust chamber 22. This point of the stroke is called the "point of release" or simply "release." By the time the piston has reached the position of release, the steam has usually expanded until its pressure is only a few pounds above the pressure of the atmosphere. As soon as the valve opens at release, the expanded steam begins to flow out of the cylinder and into the atmosphere through the exhaust pipe 24, and the pressure in the head end of the cylinder immediately falls to that of the atmosphere.

The movement of the valve to release the steam from the head end of the cylinder serves also to open communication between the crank end and the steam chest, and allows high pressure steam to flow into the crank end of the cylinder. This pushes the piston toward the head end and exhausts the steam remaining in that end of the cylinder. When the piston has nearly completed its forward stroke, the exhaust passage is closed and the remaining steam in the head end of the cylinder is compressed, thus serving as a cushion to bring the piston to rest at the end of the stroke.

From the above description it will be seen that the engine follows a regular series of operations which require two full strokes or a complete revolution of the shaft. In the order in which they occur, these operations are admission, expansion, exhaust, and compression, and they are marked by the "events" of the stroke called *admission*, *cut-off*, *release*, and *compression*.

Steam engines are usually double acting; that is, the steam acts on both sides of the piston. Thus during the forward stroke, as described above, admission and expansion are occurring in the head end of the cylinder and exhaust and compression are occurring in the crank end. During the return stroke, exhaust and compression are occurring in the head end, and admission and expansion in the crank end. Since the valve is moved automatically and distributes the steam to the ends of the cylinder, these events occur regularly and the engine runs constantly as long as steam is supplied to the steam chest.

During the cycle of the steam engine, by which we mean the

complete series of events which occur during a forward and return stroke, the steam pressure acting upon the piston undergoes many changes. If some means were provided for measuring this pressure at every part of the stroke, and if these pressures were plotted into a diagram, the diagram would appear as shown in Fig. 20.

During admission, the steam pressure is the same as that in the steam chest and is almost constant. As soon as cut-off occurs, the steam which is now confined in the cylinder begins to expand, its pressure decreasing as its volume increases. At the end of the stroke the steam in the cylinder is released and there is a sudden drop in pressure. The cylinder is now full of steam at about atmospheric pressure. During exhaust, the pressure in the cylin-

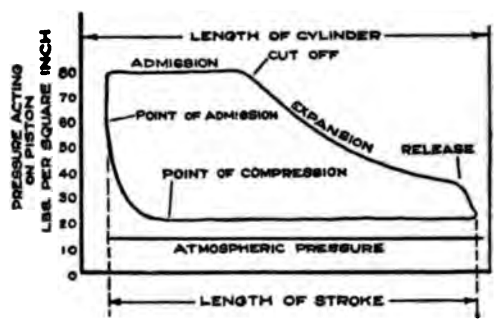

FIG. 20.

der remains constant and a little above atmospheric pressure. As soon as compression occurs, the steam which is now confined in the cylinder is compressed, causing its pressure to rise.

When the piston is at the end of each stroke there is a short distance between it and the cylinder head. The space between the piston and the cylinder head, when the piston is at the end of its stroke, and the space in the ports up to the valve, is called the clearance space or volume. The length of the stroke never equals the length of the cylinder, as a little mechanical clearance is necessary between the piston and the cylinder head, and, as the volume of the ports is large, the clearance volume will amount to from 4 to 15 per cent. of the volume swept through by the piston.

The diagram shown in Fig. 20 represents a work diagram for the steam engine, the area of this diagram representing the amount of work that is done in the head end of the cylinder during a com-

plete revolution. An instrument for drawing such diagrams is called an *indicator*, and the diagrams obtained from it are called indicator diagrams.

14. Indicators.—A common form of indicator is illustrated in Fig. 21. This indicator consists of a small steam cylinder *C*, fitted with a piston *B*, and a drum *D*, for holding a sheet of paper, both mounted on a rigid frame *A*. The steam cylinder is connected directly to one end of the engine cylinder by means of a

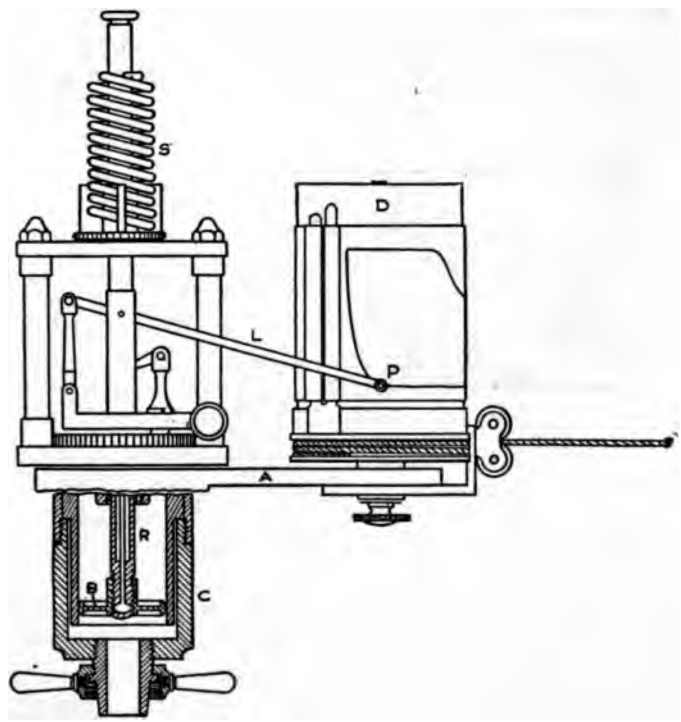

Fig. 21. Indicator.

short pipe, and hence, the same pressure that acts upon the engine piston also acts upon the indicator piston. The indicator piston and its rod, *R*, are held down by a spring *S*. To the piston rod *R* is attached a pencil arm *L* with a pencil *P* which bears against the drum. Steam or gas pressure acting upon the piston raises it to a height proportional to the pressure; therefore, the height of the pencil point indicates the pressure in the cylinder of the engine.

Several springs are furnished with each indicator, each spring being marked with a number which shows the number of pounds pressure on the piston that will be required to raise the pencil point one inch. Thus, if the spring on the indicator is marked 60, each inch of height on the indicator diagram will represent 60 pounds pressure per square inch.

The drum D turns about an axis parallel to the steam cylinder. Around the bottom of the drum is wrapped a cord which is connected with the crosshead of the engine and moves with it, thus rotating the drum back and forth in unison with the motion of the crosshead. Inside the drum is a coil spring which is wound up as the cord is pulled out and which unwinds and turns

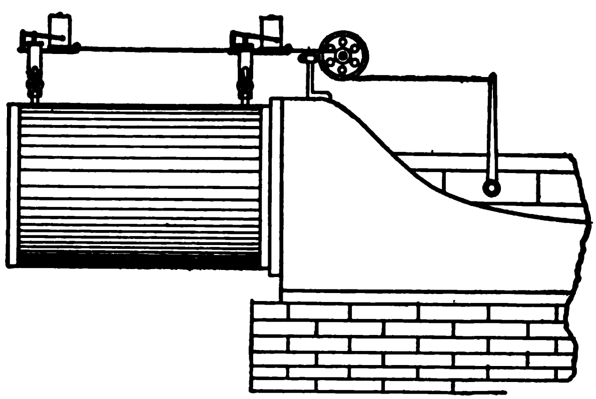

FIG. 22. Indicators mounted on engine.

the drum as the crosshead moves forward. Since the drum moves in unison with the engine piston and the pencil point indicates the pressure inside the engine cylinder, the two acting together will trace a diagram upon the drum which shows the pressure at all parts of both strokes of the piston, and, if two indicators are used, one attached to the head end of the engine cylinder and the other to the crank end, a complete record of the work being done in the cylinder will be obtained.

Since the circumference of the drum is much less than the length of stroke of the engine, it is necessary to reduce the motion of the crosshead in transmitting it to the drum. One method of mounting indicators on an engine, which also shows a device for reducing the motion of the crosshead, is illustrated in Fig. 22.

The reducing motion consists of a large and a small wheel mounted on the same shaft and fitted with a coil spring similar to that in the drum of the indicator, and serving to turn the wheels when the crosshead makes its return stroke. Thus the motion of the drum is an exact reproduction of the motion of the crosshead, but on a smaller scale.

15. Indicator Diagrams.—The paper card used upon the drum of an indicator, upon which the work diagram is drawn, is called an *indicator card*, and the diagram itself is called the *indicator diagram*. The form of diagram obtained from one type of steam engine is shown in Fig. 20. The atmospheric pressure line is

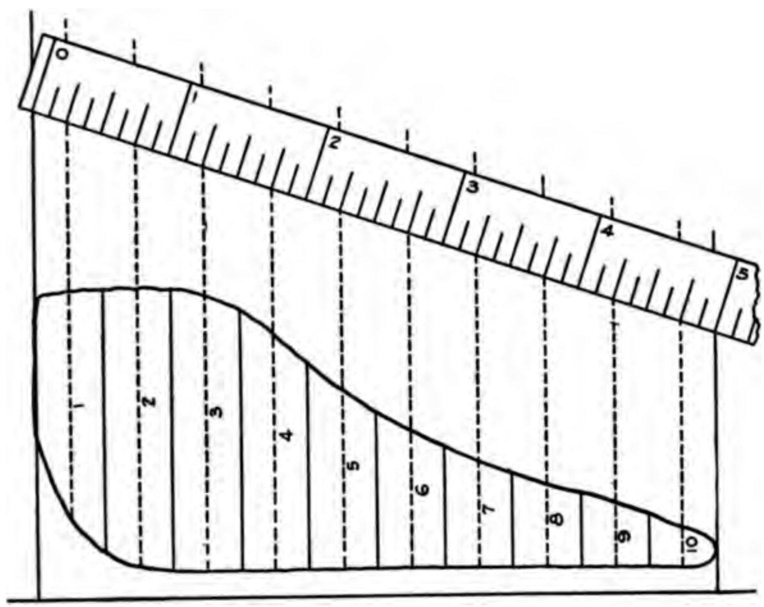

Fig. 23.

drawn by holding the pencil point to the drum before steam is turned into the indicator. Since only the pressure of the atmosphere is acting upon the indicator piston, the height of this line will represent the pressure of the atmosphere. This line is used as a reference line from which to measure other pressures, and also to measure the length of the stroke.

After the atmospheric line is drawn, steam is turned into the indicator cylinder and the pencil point is held against the drum

while the engine makes one complete revolution. The varying pressure in the cylinder will cause a diagram such as that shown in Fig. 20, to be drawn.

Since this diagram is drawn with one dimension representing pressure or force, and the other dimension representing distance, its area represents the work done in one end of the cylinder during one revolution, and from it the power developed by the engine may be calculated.

Indicator diagrams are used not only for calculating the power developed by an engine, but also to show whether the valves are working properly, since any irregularity in the operation of the valves will affect the pressure of the steam in the cylinder and hence will be recorded on the indicator diagram.

16. Mean Effective Pressure.—If the work diagram were a rectangle, its area could be found by multiplying together its height and its length, but, when the diagram has an irregular shape such as that of an indicator diagram, its *average height* must be found and this multiplied by the length. The average height of an indicator diagram reduced to pounds per sq. in. is called the *mean effective pressure*, abbreviated M.E.P.

One method of finding the M.E.P. of an indicator diagram is illustrated in Fig. 23. In this method the length of the diagram is divided by perpendicular lines into 10 equal parts and the height of the diagram is measured at the middle of each of these parts. The middle of the parts is chosen in order to secure the average height at the ends of the diagram where the pressure changes rapidly. By adding the heights of the diagram measured at the 10 points thus obtained and dividing the sum by 10, the average height is obtained. Multiplying the average height by the scale to which the pressures are drawn will give the M.E.P.

To obtain the centers of the ten spaces previously mentioned a convenient method is to take an ordinary scale and place it as shown in Fig. 24 so that the diagonal length between the limits of the diagram will be exactly 5 inches. Then at the left of the scale point off at ¼ inch, and from there on every ½ inch, toward the right of the diagram. The last point will be at 4¾ inches. From these points draw vertical lines through the diagram.

17. Indicated Horse-power.—The indicated horse-power (abbreviated I.H.P.) is the horse-power calculated from the indicator diagram. It is therefore the power developed in the

cylinder of an engine. The indicated horse-power may be calculated from the formula:

$$I.H.P.=\frac{Plan}{33{,}000}$$

in which

P = the mean effective pressure in lb. per sq. in.
l = the length of the stroke in feet
a = the area of the piston in sq. in.
n = the number of revolutions per minute.

Since the mean effective pressure is obtained from a diagram taken from one end of the cylinder, the above formula gives the I.H.P. for only one end of the cylinder. If the engine is double acting, the total horse-power developed in the cylinder is found by calculating the I.H.P. for each end of the cylinder and taking their sum. In calculating the area of the piston, it should be remembered that the steam acts upon the full area of the head end, but on the crank end the piston rod reduces the area upon which the steam pressure acts.

Example:

A 20″×38″ engine (20″ diameter of piston and 38″ length of stroke) with a 3¼″ piston rod makes 90 revolutions per minute. The M.E.P. on the head end is 64.3 lb. per sq. in. and on the crank end 66.0 lb. per sq. in. What is the indicated horse-power?

Solution:

Head end	Crank end
M.E.P. = 64.3 lb.	M.E.P. = 66.0 lb.
Length of stroke = 38″ = $\frac{38}{12}$ ft.	Length of stroke = 38″ = $\frac{38}{12}$ ft.
Area of piston = 62.83 sq. in.	Area of piston rod = 8.3 sq. in.
R.P.M. = 90	Area of piston = 62.83 − 8.3 = 54.53 sq. in.
	R.P.M. = 90

$$I.H.P. =\frac{Plar}{33{,}000}$$

$$=\frac{64.3\times38\times62.83\times90}{33{,}000\times12}$$

$$=34.95$$

$$I.H.P.=\frac{66\times38\times54.53\times90}{33{,}000\times12}$$

$$=31.15$$

Total I.H.P. = 34.95 + 31.15 = 66.1 horse-power.

For approximate calculations the average M.E.P. and area of piston may be used in the following formula:

$$I.H.P. = 2\,\frac{Plan}{33{,}000}$$

QUESTIONS

11. A pile driver has a weight of 4000 pounds which falls a distance of 15 feet and in doing so drives a pile 5 inches. With what force does the earth resist the motion of the pile?

12. Explain in your own words the difference between work and power.

13. A city of 25,000 people uses an average of 180 gallons of water for each person per day of 24 hours. If the water is pumped a height of 65 feet how many horse-power are required to run the pump? (Note. A gallon of water weighs $8\frac{1}{3}$ pounds.)

14. A man weighing 185 pounds runs to the top of a hill 120 feet high in 5 minutes. Another man weighing 130 pounds walks up the same hill in 15 minutes and carries a weight of 55 pounds. Which of the two men does more work? Which of the men develops more power?

15. What is meant by M.E.P. and how is it determined?

16. The steam engine from which the indicator diagram shown in Fig. 23 was taken is a 20″×30″ double acting engine running at 130 r.p.m. The spring used in taking the diagram was No. 60. What was the total I.H.P. developed by the engine?

17. Why does the area of an indicator diagram represent work?

18. Niagara Falls is about 160 feet high. It is estimated that about 12,000 tons of water pass over the falls each second. How many horse-power should this falling water develop?

19. Name the reciprocating parts of a steam engine.

20. What are the uses of an indicator?

CHAPTER III

HEAT ENERGY

18. Energy.—Work may be stored in a substance in such manner that it may be used afterward. For example, if the weight A in Fig. 24 is lifted from its original position A' to the position A, the work performed upon the weight in lifting it is stored in the weight, and may be used by fastening it to the rope which passes over the pulley and then allowing the weight to fall and, at the same time, to lift the weight B. By this means, work is first stored in the weight A and this stored work is used later in lifting the weight B. Work that has been stored in a substance is called *energy*. Energy may also be defined as the ability to do work, since work stored up is capable of being used again. *Anything that is capable of doing work possesses energy.*

Since energy may be changed into work and work changed into energy, these two quantities are usually measured by the same unit, the foot-pound. If the weight A in Fig. 24 weighs 1000 pounds and it is lifted a distance of 10 feet in moving from A' to A, then $1000 \times 10 (= 10{,}000)$ foot-pounds of work are performed upon it, and, in the position A, the weight contains 10,000 foot-pounds of energy.

In the example mentioned above the energy possessed by the weight after it is lifted is due to its advantageous position. This kind of energy is called *potential* energy, or the energy of position. A moving body is also capable of doing work and therefore it possesses energy. For example, when a nail is driven into a piece of wood by a hammer, the work of forcing the nail into the wood is supplied by the energy of the moving hammer. The amount of energy possessed by a moving body depends upon its weight and velocity. A heavy body moving at a low velocity may contain a large amount of energy and also a light body moving at a high velocity may contain a large amount of energy. A cannon ball rolling slowly along the ground has been known to cut off a man's leg. In this case the energy of the cannon ball was due to its weight. On the other hand, a bullet fired from

a rifle will penetrate several inches of wood. Although the weight of the bullet is small it contains considerable energy due to its high velocity. Energy which is due to the motion of a body is called *kinetic energy.*

The examples of energy mentioned above are due to the mechanical motion or condition of the body and energy which comes from this source is called *mechanical energy.* There are other kinds of energy due to the condition of a substance. A substance charged with electricity possesses *electrical energy,* a chemical compound possesses *chemical energy,* and a substance containing heat possesses *thermal energy.* In this course we are particularly interested in thermal energy.

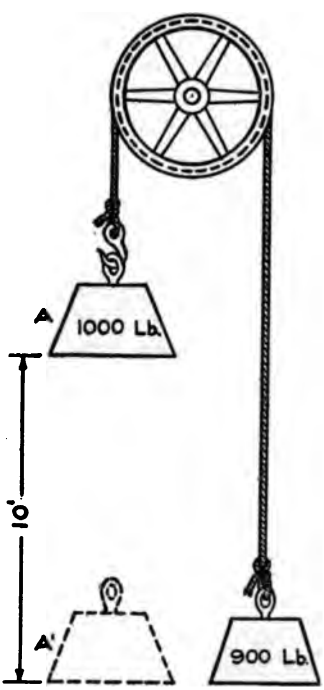

FIG. 24.

19. Heat.—It is supposed that all substances are composed of a large number of very small particles called *molecules,* which are too small to be seen, even with the aid of a microscope. There is a certain force of attraction between the molecules which causes them to cling together and thus causes the solid to retain its shape. Each molecule is in continual motion, vibrating through a very small distance and striking against other molecules in its path, then rebounding and again striking other molecules. The vibration of the molecules is caused by heat. The more heat there is in the body, the faster the molecules vibrate. If a solid substance is heated, the molecules composing it vibrate faster and therefore strike more blows in a given time, thus raising the temperature of the substance by the impact of the molecules against each other. This method of increasing the temperature of a substance may be illustrated by the following simple experiment. Place an ordinary nail on an anvil and strike the nail rapidly with a hammer. It will be observed that the nail becomes quite hot. In the same way,

the blows of molecules upon each other, when a substance is heated, cause the temperature of the substance to increase. If the heating is continued, the molecules vibrate faster and faster, until the force of the blows creates an internal pressure which is sufficient to overcome the attraction of one molecule for another, and the solid changes into a liquid.

From the above explanation it will be seen that heat is a form of energy. Heat, or thermal energy, is a form of *kinetic* energy, since it is the energy of vibrating molecules.

It is important to remember that *temperature* is not heat, but is only one of the *effects* of heat, and also that heat is not temperature. The more heat that is added to a substance (provided its condition is not changed, as from a solid to a liquid), the faster its molecules will vibrate and the higher its temperature will rise. Conversely, the more heat that is taken from a substance, the slower its molecules will vibrate and the lower its temperature will fall. If we could cool a substance to the absolute zero of temperature, it would contain *no* heat and the vibration of the molecules would stop.

While people are accustomed to use the term *cold* in the same way that the term *heat* is used, it will be understood from the above discussion that *cold* is merely an absence of heat, although in some cases it is convenient to use the word *cold* as though it meant something distinct from heat. Thus, in connection with refrigeration, we speak of the "production of cold," meaning the removal of heat or the production of low temperature.

20. Changes of Energy.—While there are different forms or kinds of energy, any one kind may be changed into any other kind. Examples of one kind of energy being changed into another are seen every day, although we do not think of them as being changes of energy. A swinging pendulum, as shown in Fig. 25, represents a change of potential energy into kinetic energy and kinetic energy back again into potential energy. At the end of its swing, when the weight is in the position A, it contains potential energy due to having been raised from the level B to the level A. At the middle of its swing, when the weight has reached its lowest point, all of the potential energy has been changed into kinetic energy. In swinging from the position B to the position C, the kinetic energy is changed again into potential energy.

A shaft turning in a bearing will become hot unless supplied

with oil to reduce the friction. In this case a part of the mechanical energy of the turning shaft is changed into heat energy.

An electric generator receives mechanical energy from a steam engine or water wheel and changes it into electrical energy. The electrical energy may then be carried on wires to lamps where it is changed into heat energy which increases the temperature of the filament until it is incandescent, or gives off light. Electrical energy may be changed into mechanical energy by means of an electric motor.

Heat energy may be changed into electrical energy by means of a joint made of two dissimilar metals. A device of this kind is

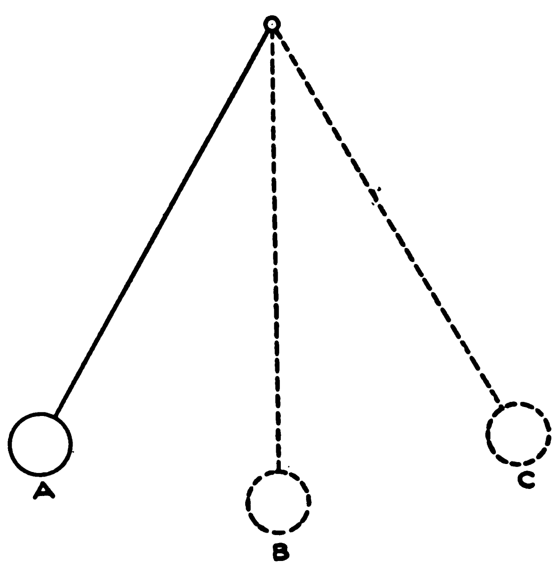

FIG. 25. Pendulum.

shown in Fig. 4, which illustrates a Le Chatelier pyrometer. Heating the "element" in this pyrometer causes a current of electricity to flow through the wires connected to it. The heat from the sun is constantly being changed into mechanical energy by evaporating water from the surface of the earth and by causing the water to fall in the form of rain which supplies the rivers and waterfalls. The heat of the sun also causes the winds, which possess mechanical energy.

The steam engine, steam turbine, and gas engine are all

devices for changing heat energy into mechanical energy. In the case of a steam engine, the heat from the fire under the boiler passes into water contained in the boiler and causes the water to change into steam, the pressure of which moves the engine piston. The pressure of the steam is due to the heat which it contains. If the steam contains a large quantity of heat, its pressure will be high and it will be capable of performing a large amount of work, but if the steam contains a smaller quantity of heat its pressure will be lower and it will be capable of performing a smaller amount of work. When the steam performs work in the cylinder of an engine some of its heat energy disappears and the exhaust steam leaving the cylinder contains less heat than when it entered the cylinder.

In a gas engine there are two transformations of energy. First, the gas or gasoline is exploded or burned in the cylinder and its chemical energy thereby changed into heat energy. This increases the temperature and therefore the pressure of the gases in the cylinder. Second, these gases then move the piston, and in doing so their temperature falls, because some of their heat energy is changed into the mechanical energy of the moving piston. At the end of the piston stroke the gases in the cylinder are cooler than at the beginning of the stroke, showing that some of their heat energy has disappeared.

21. Conservation of Energy.—Although any kind of energy may be changed into any other kind, and these changes may occur any number of times, no energy is ever destroyed or created during the process. This gives rise to the theory of the conservation of energy, which is, *that the total amount of energy in the Universe is constant, and that energy cannot be created or destroyed.*

It sometimes appears that some of the energy put into a machine is destroyed, but a close examination will show that the total amount of energy obtained from the machine is the same as that put into it. Thus the amount of energy obtained from the fly-wheel of a steam engine is considerably less than the amount supplied to the cylinder. Some of the energy is wasted in the exhaust, some is wasted in friction of the moving parts, and some is wasted in radiation of heat from the engine. The sum of these amounts of energy, together with that delivered, will equal in amount that which was delivered to the cylinder. While large amounts of energy may be wasted or dissipated, none is destroyed. "Waste of energy" is very common, but this does not mean de-

struction of energy. When we speak of "unavoidable waste" of energy, we refer to that energy which has been changed into some other form which, for our purpose, is useless. Energy may be changed from one form into another, and it tends constantly to become less and less available, but so far as is known it has never been created or destroyed.

22. Perpetual Motion.—A perpetual motion machine means either one of two things: first, that a machine, once started, can continue to run forever without the addition of energy; or, second, that a machine can give out more energy than is put into it. Every machine dissipates energy in the form of heat due to the friction of its parts. Hence a perpetual motion machine demands a *creation* of energy. The law of conservation of energy, which is well established, states that energy cannot be created. It must be concluded, therefore, that a perpetual motion machine cannot be made.

23. Unit of Heat.—Since energy is invisible, it cannot be measured directly but must be measured by its effects. Heat, being a form of energy, is measured by its effect in raising the temperature of water. The name of the unit of quantity of heat is the British Thermal Unit (abbreviated B.T.U.), and it is defined as the amount of heat which will raise one pound of pure water from 62° F. to 63° F. In defining the unit of heat it is necessary to specify the temperature of the water because the amount of heat necessary to raise the temperature of one pound of water through one degree varies slightly at different temperatures. This variation is so slight, however, that for most practical problems the B.T.U. may be taken as the quantity of heat required to raise the temperature of one pound of water one degree, without reference to any particular temperature.

Examples:

1. How much heat is required to raise the temperature of one pound of water from 32° F., its freezing temperature, to 212° F., its boiling temperature?

Solution:

Change in temperature of water equals $212° - 32° = 180°$. Heat required equals $180° \times 1$ lb. $= 180$ B.T.U.

2. What quantity of heat is required to raise the temperature of 1 gallon of water (8.34 lbs.) from 60° to 200° F.?

Solution:

Change in temperature equals $200° - 60° = 140°$. Heat required $= 140 \times 8.34 = 1167.6$ B.T.U.

24. Mechanical Equivalent of Heat.—It has been shown that heat is a form of energy; therefore it may be changed into work. Work may also be changed into heat. In either case there is a definite relation between the amount of work that may be obtained and the amount of heat expended or between the amount of heat obtained and the work expended. Experiment shows that one British Thermal Unit is equivalent to 778 foot-pounds of work. That is, 778 foot-pounds of work may be obtained from one B.T.U. The quantity 778 is called the *mechanical equivalent* of one heat unit. This number is useful in changing foot-pounds of work into heat units or heat units into foot-pounds of work. In order to change a number of heat units into foot-pounds, the number of heat units should be multiplied by 778. In order to change a number of foot-pounds into heat units, divide the number of foot-pounds by 778.

Examples:

1. One pound of a certain kind of coal has a heating value of 12,500 B.T.U. How many foot-pounds of energy does this represent?

Solution:

$12{,}500 \times 778 = 9{,}725{,}000$ ft.-lb.

2. How many heat units are equivalent to one horse-power acting for one hour?

Solution:

3. One horse-power = 33,000 foot-pounds per minute. One horse-power acting for one hour $= 33{,}000 \times 60 = 1{,}980{,}000$ foot-pounds. 1,980,000 ft.-lbs. $= \frac{1{,}980{,}000}{778} = 2545$ B.T.U.

In finding a relation between British thermal units and horse-power, it should be remembered that the heat unit is a unit of energy or work and is expressed in foot-pounds, while the horse-power is a unit of power and is expressed in foot-pounds per unit of time; therefore, in order to change from one to the other, the horse-power must be multiplied by the time or the B.T.U. divided by the time.

25. Brake Horse-power.—The power delivered at the fly-wheel of an engine is called the *brake horse-power* (abbreviated *B.H.P.*) and it represents, therefore, the net power delivered by the engine exclusive of the power wasted in overcoming the friction of its moving parts. The brake horse-power is always less than the indicated horse-power, the difference between these two quantities being the power required to overcome the

friction of the engine. The difference between the indicated horse-power and the brake horse-power is sometimes called the *friction horse-power.*

26. Measuring Brake Horse-power.—Brake horse-power is usually measured by means of some device which acts as a brake on the fly-wheel and changes the work of the engine into friction. There are various forms of friction brakes for this purpose, one of the most common of which is the Prony brake, shown in Fig. 26. This form of brake consists of a number of wooden blocks attached to a strap, *B*, and bearing against the rim of the fly-wheel. The strap is connected to a beam, *C*, in such

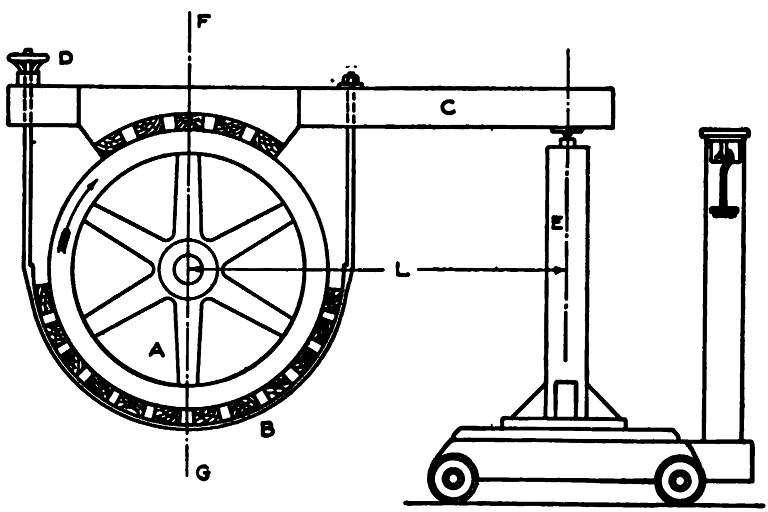

FIG. 26. Prony brake.

manner that by turning the hand wheel, *D*, the blocks are made to press more tightly against the fly-wheel and thus develop more friction. The end of the beam, *C*, rests on the standard, *E*, which is placed on a platform scales. When the fly-wheel turns in the direction shown by the arrow, the brake is prevented from turning and the force to overcome the friction between the brake and the fly-wheel is weighed on the scales. The weight indicated by the scales includes the above force and also the weight of the standard, *E*, and the unbalanced weight of the beam, *C*. Therefore the force of the friction is equal to the total weight indicated by the scales minus the weight of the standard, E, and

the unbalanced weight of the beam, *C*, which may be measured by resting the end of the beam on the scales while the brake is supported by a rope at the point along the line *FG*.

Calling the force exerted by the friction upon the scales *W*, the distance from the center of the fly-wheel to the point of support of the beam *L*, and the number of revolutions of the fly-wheel per minute *N*, the brake horse-power may be calculated by the formula:

$$\text{B.H.P.} = \frac{2\pi WLN}{33{,}000}$$

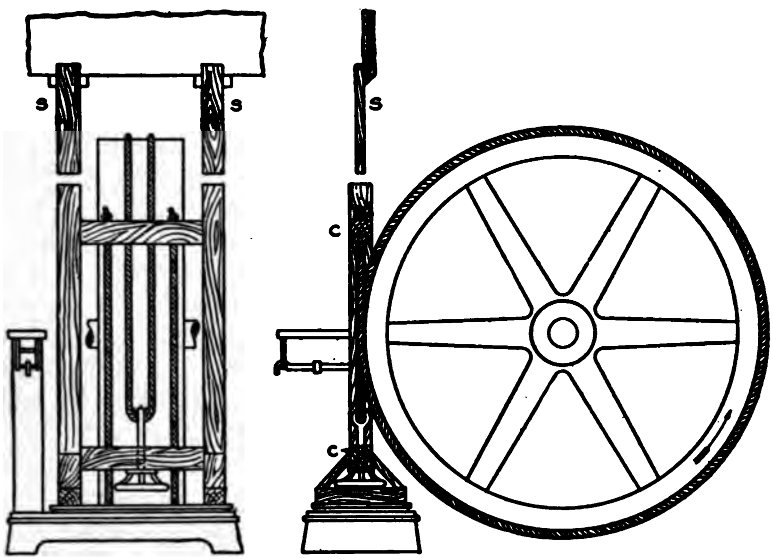

Fig. 27. Rope brake.

In which W = force of friction as measured by the scales, in pounds
L = distance in feet from center of fly-wheel to point of support of the beam
N = number of revolutions per minute

Example:

What is the brake horse-power of a steam engine running at 210 R.P.M. when fitted with a Prony brake which measures 8 feet from the center of the fly-wheel to the point of support at the end of the arm, the scale reading 742 pounds, the unbalanced weight of the brake arm being 13 pounds, and the weight of the standard being 10 pounds?

Solution:

$$\text{B.H.P.} = \frac{2\pi WLN}{33{,}000}$$

$$W = 742 - 13 - 10 = 719 \text{ pounds}$$

$$N = 210 \text{ R.P.M.}$$

$$L = 8 \text{ ft.}$$

$$\text{B.H.P.} = \frac{2\pi \times 719 \times 210}{33{,}000} = 230 \text{ B.H.P.}$$

In order to load an engine with a brake, the band is tightened until the engine barely maintains full speed and the band is then kept just tight enough to maintain a constant speed.

Since the work done by an engine loaded with a brake is turned into heat at the fly-wheel, some arrangement must be provided for cooling the fly-wheel to prevent its being overheated. This is usually done by providing a special wheel on which the brake is placed, this wheel having fins at the edge of the rim, projecting inward and forming a trough into which a small stream of water is run. The water is run into the trough by a pipe at one point and scooped up at another point by a second pipe.

Another form of brake for measuring power is shown in Fig. 27. This form of brake is called a rope brake, because the friction which furnishes the load is produced by a rope wound around the fly-wheel. In this brake the ends of the rope are attached to the top cross piece C of a wooden frame which rests on a platform scales. The rope is looped around the fly-wheel and the middle attached to a screw which passes through the bottom cross piece, C. This screw passes through a hand wheel, which is used to tighten the rope and thus regulate the load on the engine. Instead of a hand wheel, a large nut may be used for this purpose.

The brake horse-power, as measured with this form of brake, may be calculated from the following formula:

$$\text{B.H.P.} = \frac{2\pi RWN}{33{,}000}$$

in which R = radius of brake or distance from center of wheel to center of rope, in feet

W = load on scales in pounds = weight indicated by scales minus weight of wooden frame

N = number of revolutions per minute

27. Specific Heat.—The specific heat of a substance is the

number of B.T.U. required to raise the temperature of one pound of the substance through one degree Fahrenheit. Experiment shows that when equal weights of various substances are heated through the same range of temperature they absorb different amounts of heat, which shows that the specific heat of different substances is not the same. This fact may be proved by the following simple experiment. Provide two glass vessels containing equal amounts of water at the same temperature. Then take one pound each of copper and of iron and heat them to the same temperature. Put the copper in one of the vessels of water and the iron in the other. It will be found that the water into which the iron is put will reach a higher temperature than that into which the copper has been put, showing that the pound of iron contains more heat for an equal temperature than the pound of copper, or, in other words, the specific heat of the iron is higher than that of the copper.

From the definitions of specific heat and of a heat unit, it will be seen that the specific heat of water is one (1). The specific heat of practically all other substances is less than that of water, showing that water has a greater capacity for absorbing heat than almost any other substance. The following table gives the specific heats of some of the more common solids and liquids.

SPECIFIC HEATS OF SOLIDS AND LIQUIDS

Solid	Specific heat	Liquid	Specific heat
Aluminium	.2158	Water	1.000
Antimony	.0489	Alcohol (grain)	.6480
Brass	.08831	Alcohol (wood)	.6010
Cast iron	.1189	Benzine	.4500
Charcoal	.2410	Bismuth (melted)	.0308
Copper	.0951	Ether	.529
Glass	.1988	Fusel oil	.564
Gold	.0316	Glycerine	.576
Ice	.504	Lead (melted)	.0356
Lead	.0305	Mercury	.0333
Nickel	.1128	Petroleum	.511
Paraffine	.6939	Sulphur (melted)	.2350
Platinum	.0323	Sulphuric acid	.3350
Phosphorus	.1829	Tin (melted)	.0599
Silver	.0559	Turpentine	.441
Steel (soft)	.1165		
Steel (hard)	.1175		
Sulphur	.137		
Tin	.0518		
Wrought iron	.1152		
Zinc	.0931		

The above table would indicate that the specific heat of the substance given is constant. This, however, is not the case, the specific heat varying slightly at different temperatures. The values given in the table are for the ordinary temperatures dealt with in engineering work.

The number of B.T.U. absorbed by a substance in raising its temperature, or given up in lowering its temperature through any number of degrees may be calculated by multiplying together the weight of the substance, its specific heat, and the range of temperature through which it is heated or cooled. Expressed as a formula:

$$H = Ws\ (t_2 - t_1)$$

In which H = number of heat units absorbed or given up
W = weight of the substance in pounds
s = specific heat of the substance
t_2 = higher temperature
t_1 = lower temperature

The above rule does not apply when the substance changes its state, as from a solid to a liquid, or from a liquid to a solid.

Example:

How many heat units are required to raise the temperature of a cast iron boiler weighing 1800 pounds from a temperature of 60° F. to a temperature of 320° F.?

Solution:

Weight to be heated = 1800 pounds
Range of temperature = 320° − 60° = 260°
Specific heat of cast iron = .1189
$H = 1800 \times .1189 \times 260$
$= 55{,}645$ B.T.U.

In order to calculate the weight of a substance which can be heated or cooled through a given range of temperature by a certain amount of heat, the following formula may be used:

$$W = \frac{H}{s\ (t_2 - t_1)}$$

in which the letters have the same meaning as before. In this formula the quantity $s\ (t_2 - t_1)$ represents the number of B.T.U. absorbed in raising the temperature of one pound of a substance from t_1 to t_2 degrees, or the number of B.T.U. given up by one pound of a substance in cooling from t_2 to t_1 degrees. This quantity divided into the total amount of heat, H, absorbed or given up, gives the weight, W, of the substance heated or cooled.

Example:

How many pounds of copper may be heated from 40° F. to 120° F. by 30 B.T.U.?

Solution:

Amount of heat absorbed by the copper = 30 B.T.U.
Specific heat of copper = .0951
Range of temperature = 120° − 40° = 80°

$$W=\frac{30}{.0951\times 80}=\frac{30}{7.608}=3.943 \text{ pounds}$$

28. Resulting Temperature of Mixtures.—If a mixture is made of two substances having different temperatures, both substances will assume the same temperature, which will be intermediate between the original temperatures of the substances. The following formula may be used for calculating the final temperature of a mixture of two substances:

$$T=\frac{WSt_2+wst_1}{WS+ws}$$

in which T = final temperature of the mixture
t_2 = temperature of hotter substance
t_1 = temperature of cooler substance
W = weight of hotter substance
w = weight of cooler substance
S = specific heat of hotter substance
s = specific heat of cooler substance

In the above formula the quantity WSt_2 is the amount of heat above zero which one of the substances contains, and wst is the amount of heat above zero which the other substance contains. The sum of these two quantities, or WSt_2+wst_1, is the total amount of heat in the mixture of the two substances. The quantity $WS+ws$ is the heat capacity of the mixture for each degree of temperature. Therefore, dividing WSt_2+wst_1 by $WS+ws$ gives the final temperature resulting from the mixture of the two substances.

Example:

If 2000 pounds of water having a temperature of 200° F. are poured into a cast iron vessel weighing 3000 pounds and having a temperature of 50° F., what will be the final temperature of the water? Neglect loss of heat by radiation.

Solution:

Weight of water = 2000 lbs.
Temperature of water = 200° F.
Specific heat of water = 1
Weight of cast iron = 3000
Temperature of cast iron = 50° F.
Specific heat of cast iron = .1189

$$T=\frac{WSt_2+wst_1}{WS+ws}$$

$$=\frac{(2000\times1\times200)+(3000\times.1189\times50)}{(2000\times1)+(3000\times.1189)}$$

$$=\frac{400{,}000+17{,}835}{2000+357}=\frac{417{,}835}{2357}=177.2°\,F.$$

QUESTIONS

21. Explain in your own words the difference between power and energy.

22. What is the difference between potential and kinetic energy?

23. What is heat? What is the difference between heat and temperature?

24. Do you think it is possible to invent a perpetual motion machine? Give the reasons for your answer.

25. Name all of the changes of energy that occur in a steam power plant generating electricity.

26. A Prony brake on the fly-wheel of a steam engine which is running at 130 R.P.M. measures 10 feet from center of fly-wheel to point of support at the end of the arm. The scales read 860 lbs. and the standard weighs 8 lbs. The unbalanced weight of the brake is 12 lbs. What is the brake horse-power of the engine?

27. If the friction horse-power of the engine mentioned in the preceding question is 24.4, how many I.H.P. does the engine develop?

28. The Prony brake mentioned in Question 26 is supplied with water having a temperature of 60° F. and the water leaves the fly-wheel at a temperature of 82° C. How many gallons of water must be supplied to the fly-wheel to keep its temperature constant?

29. A pumping engine does 68 millions foot-pounds of work by burning 112 lbs. of coal. How many pounds of coal does it consume per horse-power per hour?

30. A hard steel plate weighing 200 lbs. is to be tempered by placing it in a vessel containing 30 gallons of water which has a temperature of 15° C. The temperature of the steel plate is 226° C. What will be the temperature of the water in Fahrenheit degrees after the steel plate has been immersed in it?

CHAPTER IV

TRANSFERRING AND MEASURING HEAT

29. Conduction.—When any substance is heated there is always a tendency for the heat to spread throughout the substance and in this way to cause all parts of it to reach the same temperature. This indicates that heat may flow or be transferred from one point to another, and such is, indeed, the case. Heat may be transferred from one point to another in three ways: by *conduction*, by *convection*, or by *radiation*. Only one of these agencies may be acting at one time to transfer heat, but usually two or all three of them are acting at the same time.

If one end of an iron rod is held in a fire the other end will soon become hot. The process by which heat travels from one end of the rod to the other is called *conduction*. Conduction is a method of transferring heat by which one molecule of a substance becomes heated and passes on a part of its heat to the next molecule, which comes in contact with it, and which has a lower temperature. The reason that conduction takes place is because there is always a tendency for heat to become degraded or lowered in temperature, which represents the *intensity* of the heat, or for it to flow from a point of high temperature to a point of low temperature. In the case of the rod mentioned above, that part of the rod which is in the fire assumes a high temperature; the adjacent part of the rod has a lower temperature, hence the heat passes from the hot end toward the cold end.

It must not be inferred that the tendency of heat to pass through the body of a substance is the same in all substances. In general, the metals are better conductors of heat than other substances. It is a well-known fact that a lighted match may be held between the fingers for 30 or 40 seconds, but, if a copper rod of the same size as the match is held with one end in a match flame, the other end becomes so hot in a few seconds that it cannot be held, showing that copper is a much better conductor of heat than wood. It is a peculiar fact that those

substances which are good conductors of heat are also good conductors of electricity.

Even the metals themselves differ in their ability to conduct heat, as may be shown by the following experiment. A copper and an iron wire of equal length are twisted together as shown in Fig. 28 and a number of steel bicycle balls are attached to the wires at equal intervals by means of wax. A flame is applied to the ends of the wires that are twisted together, thus heating both wires to the same temperature. As the wires become

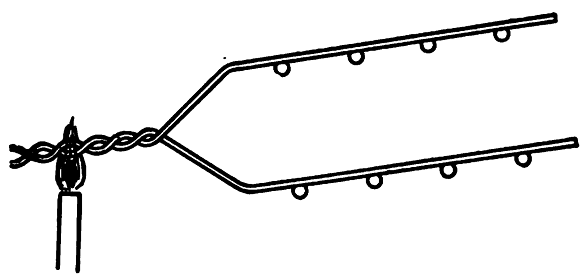

FIG. 28.

heated the wax will melt, allowing the bicycle balls to drop, those nearest the flame dropping first. It will be noticed that the balls attached to the copper wire drop before those attached to the iron wire, showing that copper is a better conductor of heat than iron.

The following table shows the relative conductivity of various substances, that of silver being taken as 100:

TABLE OF RELATIVE HEAT CONDUCTIVITIES

Silver	100
Copper	74
Gold	53
Brass	27
Tin	15
Iron	12
Lead	8.5
German silver	6.3
Mercury	1.35
Ice	.21
Glass	.046
Hard rubber	.024

The actual amount of heat transferred through a substance depends not only on the kind of material but also on the length of the path through which the heat travels, upon the cross-sectional area of the material, and upon the difference in temperature at the two ends. In these respects the flow of heat through the body of a substance resembles the flow of water through a pipe, the difference in temperature acting toward the flow of heat as a difference in level does to the flow of water.

The sense of touch cannot be relied upon to determine relative conductivities any more than it can be relied upon to determine temperatures because the effect of different substances upon the sense of touch is not always the same. It is a common observation that on a cold day a piece of iron feels much colder than a piece of wood, even though both have the same temperature. On the other hand, if a piece of iron and a piece of wood have been standing in the sun on a hot day, the wood may be handled without discomfort, but the iron will feel hot. The explanation of these facts is that on a cold day the iron removes heat from the hand much faster than wood because it is a better conductor of heat, and the removal of heat from the hand produces a sensation of cold. On a hot day the iron gives up heat to the hand faster than does the wood, for the same reason, and the rapid supply of heat to the hand produces a sensation of warmth.

A good illustration of the principle of conduction of heat is to be found in the construction of the Davey miner's lamp, which is used in mines where an open flame would ignite explosive gases. In this lamp the flame is enclosed in a wire netting, usually made of fine copper wire. The network of small wires conducts the heat away from the flame so fast that the flame will not pass through it, unless ignited on the other side. If a piece of wire netting is placed over a gas jet as in Fig. 29, and the gas is ignited on top of the netting, the flame will not pass through the netting to the under side. Also if the gas is ignited below the wire netting, the flame will not pass through the netting to the upper side.

The conductivity of liquids is much less than that of solids, and the conductivity of gases is even less than that of liquids. Thus the conductivity of pure water is only about $\frac{1}{1200}$ of that of silver, while the conductivity of still air is only about $\frac{1}{25}$ of that of water, or $\frac{1}{30000}$ that of silver.

The low conductivity of liquids is illustrated in Fig. 30, in

which a tube nearly full of water is held in the hand while a gas flame is applied near the surface of the water. Although the water in the top of the tube boils, the bottom, which is held in

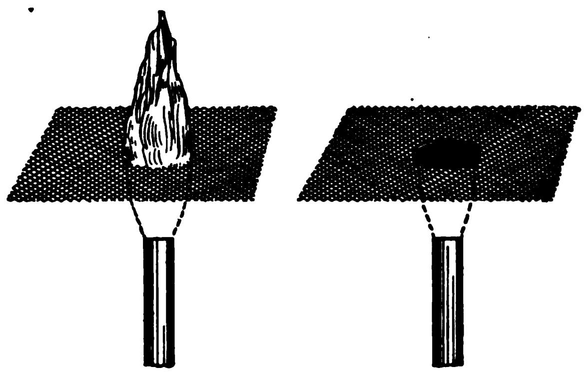

FIG. 29.

the hand, does not become hot enough to be uncomfortable to the hand, thus showing that very little heat passes through the water.

The low conductivity of still air makes it a good insulating material for cold-storage rooms. In constructing cold-storage

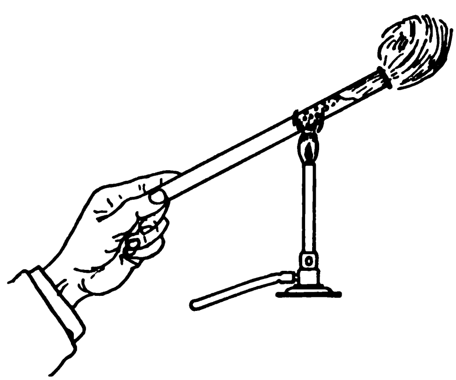

FIG. 30.

rooms the walls are sometimes made double, with a space between. This space is then filled with mill shavings. The shavings themselves have but little conductivity. The principal insulation however, is secured by the large number of small air

spaces between the shavings. These small spaces contain still air, which is one of the best insulators of heat known.

30. Convection.—Both liquids and gases have another means of transferring heat called *convection*, by means of which these substances may transfer heat more readily than by conduction. Under favorable conditions liquids may transfer heat even faster by convection than some solids can transfer it through the same distance by conduction. Convection is the process of transferring heat by a motion or circulation taking place within the body of the liquid or gas. Fig. 31 illustrates how this is done. If a gas flame be applied to the bottom and near the edge of a vessel partly filled with water, the water will be observed to move in the direction indicated by the arrows in Fig. 31, flowing upward over the point at which the gas flame is applied and flowing downward on the opposite side.

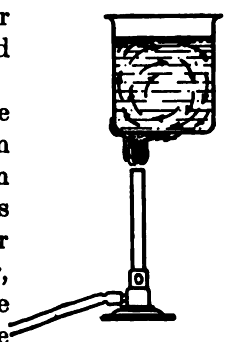

FIG. 31.

The explanation of the action taking place within the water is as follows: Heat from the gas flame passes through the bottom of the vessel by conduction, and increases the temperature of the particles of water which are nearest the flame. The water, which is thus heated, is rendered less dense or lighter, and rises to the top, while the colder and therefore heavier water comes in from the sides to take its place.

Heat cannot be transferred in solids by convection but only in liquids and gases. Convection plays a very important part, however, in heating these substances. It is often stated that dry air is one of the best insulators of heat, but this is true only when the air is prevented from moving, as by dividing the air space into small sections. If the air is allowed to circulate in an air space between two walls, heat may be carried readily from one of its walls to the other and thus prevent the air space from being a good insulator.

Air does not transfer heat by convection as readily as does water, for two reasons: first, the specific heat of water is greater than that of air, hence water will carry more heat per pound than air, and second, heat that is transferred by convection must first pass through some substance by conduction, usually a plate of

metal, and air does not absorb heat from a surface as readily as water does.

A common example of transferring heat by convection in a liquid is to be found in the hot water system of heating houses. In this system of heating, which is illustrated in Fig. 14, water is heated in a hot water heater placed in the basement and rises through pipes to the radiators located in the rooms above, where it loses a portion of its heat. Then, being cooler, it flows downward through other pipes to the heater.

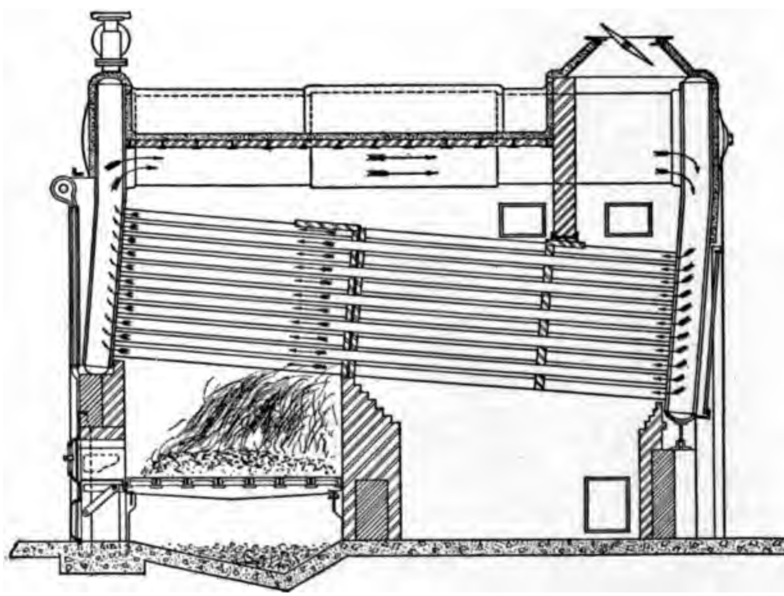

FIG. 32. Circulation of water in a water-tube boiler.

In steam boiler practice, convection is very important because the ability of the boiler to generate steam rapidly depends largely upon the convection currents in the water contained in the boiler. A very high temperature is maintained in the furnace of a steam boiler and heat is liberated from the fuel rapidly. This heat is carried over the plates and tubes of the boiler by hot gases from the furnace. These gases heat the plates and tubes to a high temperature. The heat then passes by conduction through the plates and tubes and enters the water in the boiler. By arranging the boiler in such a way that the water can sweep in a strong current over the surfaces of the plates and tubes, heat may

be transferred from the furnace to the water at an extremely rapid rate. If the convection currents in the boiler, or, as they are more commonly called, the circulation, is sluggish, the water will not be able to absorb the heat nearly as fast as it is delivered by the furnace, hence, there would be danger of the plates and tubes becoming overheated and burned. The arrangement of a steam boiler in order to promote circulation is shown in Fig. 32. The water in the front part of the boiler receives heat from the furnace, then rises to the large drum on top. It then flows

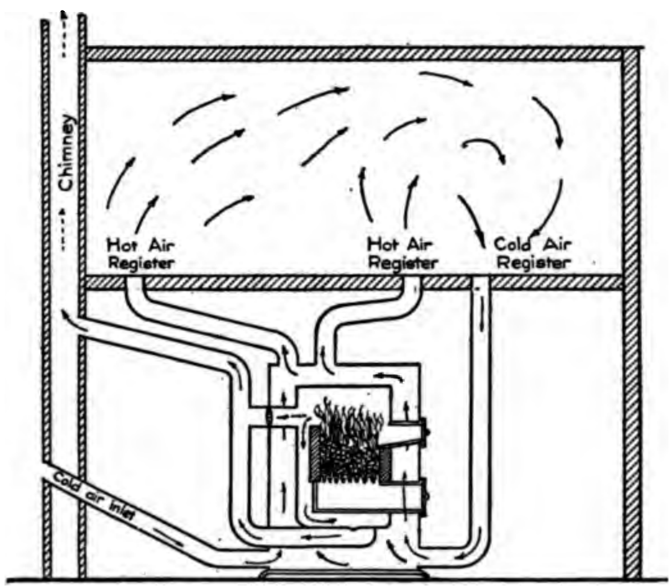

FIG. 33. Warm air furnace heating system.

through this drum to the rear and down into the tubes to receive more heat.

The method of heating houses by means of a warm air furnace is a good example of the application of transferring heat from one point to another by means of convection currents in air. This system of heating is illustrated in Fig. 33. It consists of a furnace located in the basement and of a number of pipes for conveying cold air to the furnace and warm air to the rooms that are to be heated. The cold air enters the furnace at the bottom and takes up heat from the furnace by contact with its metal parts. The warmed air then rises and passes by convection

through other pipes to the rooms above. The same air is not used over and over again, but instead, the warm air in the rooms leaks out around door and windows and through other openings, a fresh supply being taken in through the furnace from out-of-doors, to replace it.

31. Radiation.—When the hand is held beneath an electric globe, as shown in Fig. 34, the heat from the lamp may be felt. In this case the heat cannot reach the hand by conduction because the hand is not touching the globe; nor can it reach the hand by convection, because the air which would carry the heat rises when it is heated. When heat is carried across a space without the aid of any material substance, as in the above illustration, it is said to be transferred by radiation. The heat which is transferred in this way is called *radiant heat.*

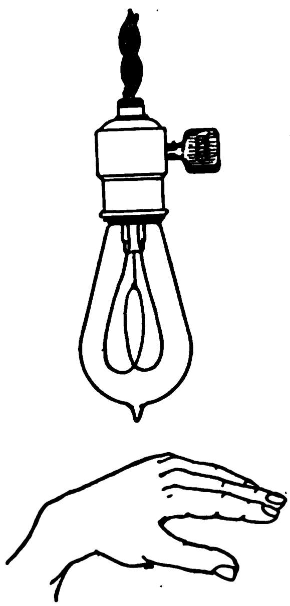

FIG. 34. Radiation.

Examples of the radiation of heat are so common that they are often unnoticed. If one sits in front of a hot fire in a fire-place, the heat which he feels comes to him by radiation. It could not come to him by convection because the currents of air are moving toward the fire. Nor can the heat be transferred to him by conduction, for he is not in contact with it.

The heat from the sun reaches the earth by radiation. As the distance from the earth to the sun is about 93,000,000 miles, and most of this space is a vacuum, convection currents could not pass from the sun to the earth.

The process of transferring heat by radiation is much more rapid than by either conduction or convection. Radiant heat travels at the same speed as light, which is 186,000 miles per second. That the speeds of light and radiant heat are the same is proved by the fact that during an eclipse of the sun the shutting off of heat takes place at the same time as the shutting off of light.

Radiation differs from conduction and convection in that radiant heat always travels in straight lines while conducted or

convected heat may follow almost any curved path. Radiant heat may be cut off by a screen, but convected heat would pass around it. Twisting or bending a metal bar does not affect heat passing through it by conduction.

Unlike conduction and convection, radiant heat may pass through a substance without heating it, or it may even pass through a vacuum. Thus, the sunlight passing through a window pane will warm a person without heating the window pane through which it passes. The sun's rays reaching the earth pass through an enormous distance which is almost a perfect vacuum, before reaching the surface of the earth. Even the atmosphere surrounding the earth receives very little heat from the sun's rays passing through it.

Radiant heat may be reflected from bright surfaces in the same manner that light is reflected, the radiant heat reaching the bright surfaces in straight lines and leaving in straight lines. In general, a surface which will reflect radiant heat readily will not absorb it readily, because most of the heat reaching the surface is reflected away again. On the other hand, those substances which absorb radiant heat readily also radiate heat readily. Dark-colored substances usually absorb radiant heat better than light-colored ones.

It follows from the above statements that a well-designed tea-kettle should be nickel plated on all parts except the bottom. This will insure a small loss of heat by radiation from the body of the tea-kettle, while allowing the bottom to absorb heat readily.

In a great many cases heat is not transferred by conduction, convection or radiation alone, but rather by a combination of two or three of these methods. When a room is heated by a hot water radiator the heat is transferred from the water to the inner surface of the radiator by conduction. It is then transferred from the inner to the outer surface by conduction through the metal of the radiator. Part of the heat, which is now at the outer surface of the radiator, is transferred to objects in the room by radiation, and the remainder is distributed by convection currents in the air which is heated by contact with the radiator and then moves away to other parts of the room where it gives up its heat by conduction or contact. In heating a kettle of water over a fire, the heat passes from the fire to the kettle by radiation and by contact of the hot gases from the fire. The

heat then passes through the metal of the kettle and into the water by conduction.

In cases where heat is transferred by a combination of conduction, convection, and radiation, the proportion of the total amount of heat transferred by any one of these means is not usually known, hence it is impossible to calculate separately the amount of heat transferred by conduction, by convection, and by radiation and then add these amounts to obtain the total amount of heat transferred. For such calculations, the amount of heat transferred per hour by all sources is found by experiment for a square foot of the material through which the heat is transferred and for a difference in temperature of one degree between the points which receive and give off the heat. This factor is then used in the following formula:

$$H = AK\ (T_1 - T)$$

in which H = Number of B.T.U. transferred in one hour

A = The square feet of surface receiving or giving off the heat

K = Number of B.T.U. transferred per hour by one square foot of the material for a difference of one degree between the two surfaces of the material

T_1 = Temperature of the surface having the higher temperature

T = Temperature of the surface having the lower temperature

Example:

It is known that the amount of heat lost from each square foot of surface of a frame dwelling house is .25 B.T.U. per degree difference of temperature between the inside and outside of the house. How much heat will be lost per hour from the wall of a room which is 12 feet long and 10 feet high when the temperature inside the room is 70° F. and the temperature outside is 0° F.?

Solution:

Area of the walls which transfers the heat

$A = 10 \times 12 = 120$ square feet

Therefore, $H = 120 \times .25\ (70 - 0)$

$= 120 \times .25 \times 70$

$= 2100$ B.T.U.

The heat lost from an entire house may be calculated in a manner similar to the above, and the heating system proportioned to supply this amount of heat. Some of the more common

values of K, which have been determined by experiment are given in the following table:

	K
Plain brick wall 12″ thick	.29
Plain brick wall 16″ thick	.25
Plain brick wall 20″ thick	.22
Walls having lath and plaster on the inside, and the outside being covered with:	
Overlapping clapboards	.44
Paper and clapboards	.31
¾″ sheathing and clapboards	.28
¾″ sheathing, clapboards and paper	.25
Other surfaces	
Window	1.00
Skylight	1.16
Lath and plaster ceiling	.62
Floor ¾″ thick with lath and plaster below	.26
1″ wooden door	.41

32. Insulation.—All substances conduct or radiate heat to a greater or less extent; hence it is impossible to entirely prevent the passage of heat through any substance, but, as shown by the table of relative conductivities given on page 50, some substances allow heat to pass through them more readily than others. Substances which allow heat to pass through them readily are said to be good *conducting* substances, and those which do not allow heat to pass through them readily are said to be good *insulating* substances.

Heat insulation plays a very important part in refrigeration, where low temperatures are maintained by the expenditure of energy in a refrigerating machine or by the melting of ice. Any heat that leaks into a cold storage compartment must be counterbalanced by the expenditure of extra energy to lower the temperature and hence involves a direct loss. In cold climates it is important to construct buildings in such a manner as to reduce the leakage of heat from them in order to reduce the expense of heating, and large sums of money are often spent to accomplish this purpose. Steam pipes are often covered with insulating material to reduce the loss of heat from them, and pipes carrying cold brine for refrigerating purposes are insulated to prevent a serious change in temperature of the brine while it is being transferred from one point to another.

Pipe covering is usually made of asbestos or magnesia, moulded to the shape of the pipe in lengths of about three feet and with a

thickness of about 1⅝ inches. The lengths are split longitudinally and are covered with canvas to protect them from injury. These lengths are then fastened on the pipe by means of brass bands placed around them. Other materials used for pipe covering are cork, hair felt, and mineral wool. When asbestos is used it is sometimes moulded with a number of small air cells running through it, the air confined in these small cells forming insulation of high value. The best insulating substance known is air confined in minute cells, and the best non-conducting coverings owe their efficiency to the numerous air cells in their structure. The following table shows the insulating value of several pipe coverings and also the loss of heat from uncovered pipe.

INSULATING VALUE OF PIPE COVERINGS

Kind of covering	Thickness of covering, inches	B.T.U. lost per sq. ft. of pipe surface per hour per degree difference of temp.	Per cent. of heat lost
Bare pipe	....	2.7	100.0
Mineral wool	1.3	.285	10.6
Hair felt	.96	.387	14.3
Solid cork	1.68	.438	12.9
Magnesia	1.25	.384	14.2
Asbestos sponge felted	1.24	.532	19.7
Asbestos air cell	1.26	.486	18.0
Asbestos fire felt	1.30	.502	18.6

Insulation of cold storage buildings and compartments is secured by the use of hair felt, granulated cork, nonpareil cork, mineral wool, rock wool, lith, pumice, cork, and pitch, or mill shavings in combination with wood, brick, cement, and air spaces. It has been demonstrated that still air is one of the best insulators, but the size of the air space must be small in order to prevent the air from moving. If a large air space exists between vertical walls the confined air will move downward along the colder wall and upward along the warmer one and a circulation is thus created which transfers heat rapidly from one wall to the other. If the air space is divided horizontally and vertically into smaller sections, the circulation of air is retarded and its insulating value increased. If the air space is further subdivided by filling with some material, such as granulated cork or mill shavings, its insulating value is still further increased.

An insulation, however good when new, will become less

effective if it becomes damp. Besides being moisture-proof, insulation should be non-odorous and unlikely to settle or to

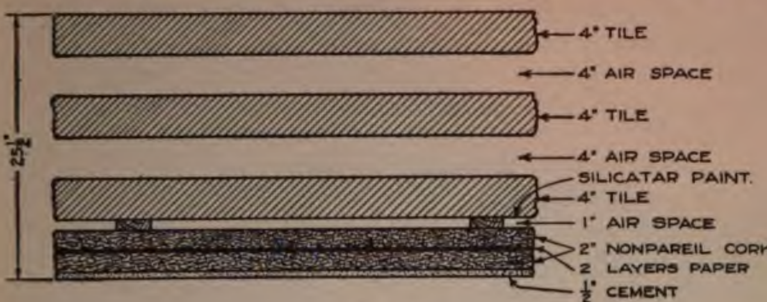

Fig. 35.

decompose. It should also be slow-burning or fire-proof and easily applied. Recently insulating papers of different kinds have been adopted in insulated structures. Their value depends

Fig. 36.

upon their ability to prevent the entrance of moisture and air rather than upon their insulating qualities. In order to prevent

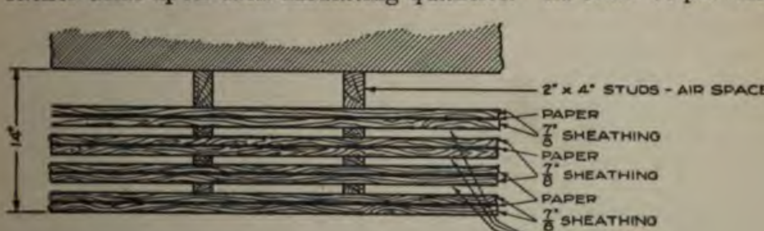

Fig. 37.

the penetration of moisture into insulation other materials such as pitch, paraffin, and so-called water-proof paints and varnishes are also used.

Figs. 35, 36, and 37 show types of modern construction for walls of refrigerated buildings. Any of these types of walls are well adapted to buildings in which the temperature is maintained at 0° F. when the outside temperature is 80° F.

The following table, originated by Mr. J. E. Starr, gives the insulating value of some common types of construction:

INSULATING VALUE OF DIFFERENT KINDS OF CONSTRUCTION

Material	B.T.U. lost per sq. ft. of surface per hr. per degree difference in temperature
Mill shavings	
⅞″ sheathing, paper, ⅞″ sheathing, 8″ mill shavings, ⅞″ sheathing, paper, ⅞″ sheathing.	.056
Same slightly moist	.075
Same damp	.087
Hair Felt	
⅞″ sheathing, paper, ⅞″ sheathing, 1″ hair felt, ⅞″ sheathing, paper, ⅞″ sheathing	.138
⅞″ sheathing, ¼″ hair felt, ⅞″ sheathing, 2 layers ¼″ hair felt, ⅞″ sheathing, ¼″ hair felt, ⅞″ sheathing	.105
Sheet Cork	
⅞″ sheathing, paper, ⅞″ sheathing, 1″ air space, 4″ sheet cork, paper, ⅞″ sheathing.	.050
Same with 5″ sheet cork	.037
⅞″ sheathing, paper, 3″ sheet cork, paper, ⅞″ sheathing.	.087
⅞″ sheathing, paper, ⅞″ sheathing, 1″ sheet cork, ⅞″ sheathing, paper, ⅞″ sheathing	.137
Granulated Cork	
⅞″ sheathing, paper, ⅞″ sheathing, 4″ granulated cork, ⅞″ sheathing, paper, ⅞″ sheathing	.071
Mineral Wool	
⅞″ sheathing, paper, 2½″ mineral wool, paper, ⅞″ sheathing	.151
Same with 1″ mineral wool	.192
Wood	
⅞″ sheathing, paper, ⅞″ sheathing, paper, ⅞″ sheathing, paper, ⅞″ sheathing	.178
Air Spaces	
⅞″ sheathing, paper, ⅞″ sheathing, 8″ air space, ⅞″ sheathing, paper, ⅞″ sheathing	.112
Pitch	
⅞″ sheathing, 1″ pitch, ⅞″ sheathing	.204
⅞″ sheathing, 2″ pitch, ⅞″ sheathing	.177

33. Measuring Heat.—The unit of heat has been defined as the quantity of heat necessary to raise the temperature of one pound of water one degree Fahrenheit (from 62° to 63°). This definition indicates a convenient way of measuring different quantities of heat, that is, by passing the heat into a known weight of water and noting the rise in temperature of the water. The quantity of heat absorbed by the water will then be equal to the product of the weight of water and its change in temperature. Devices for measuring quantities of heat are called *calorimeters*, and nearly all of them operate upon the method outlined above. Steam calorimeters are an exception to this, but they are not really heat measuring devices, but rather devices for determining the amount of moisture in steam. The kinds of calorimeters most commonly used are the coal calorimeter and gas calorimeter. The coal calorimeter is used for measuring the heating value of coal and other solid fuels and also for liquid fuels. The gas calorimeter is used for measuring the heating value of gaseous fuels.

34. Coal Calorimeter.—There are several forms of coal calorimeters which are widely used and which differ from one another in the details by which the fuel is fired, but which are all alike in the method of measuring the heat by passing it into a known weight of water and noting its rise in temperature.

One of the best-known coal calorimeters is the Mahler Bomb, which is illustrated in Fig. 38. This calorimeter consists of two parts, a steel vessel called a bomb, in which the fuel to be tested is burned, and a vessel containing water, in which the bomb is immersed. When the fuel is burned the heat that is developed passes through the walls of the bomb and into the water, thus raising its temperature.

The bomb consists of a porcelain-lined steel shell fitted with a screwed cap, the porcelain lining being for the purpose of protecting the steel shell which would be attacked by the gases from the burning fuel. To the screwed cap is attached a small platinum cup for holding the fuel, which is powdered, if solid, or is placed in a gelatin capsule, if liquid. A small iron wire is placed in contact with the fuel. The fuel is ignited by passing an electric current through the small iron wire, which heats it to redness. After the fuel is placed in the bomb, oxygen under a high pressure is pumped into it. This causes the fuel to ignite readily and burn almost instantly and completely, leaving only a pure ash.

The water in the vessel containing the bomb is stirred constantly during the test of a sample of fuel, in order to secure a uniform temperature throughout the water. The temperature of the water is read at short intervals during the test to determine its maximum increase. The vessel is protected from loss

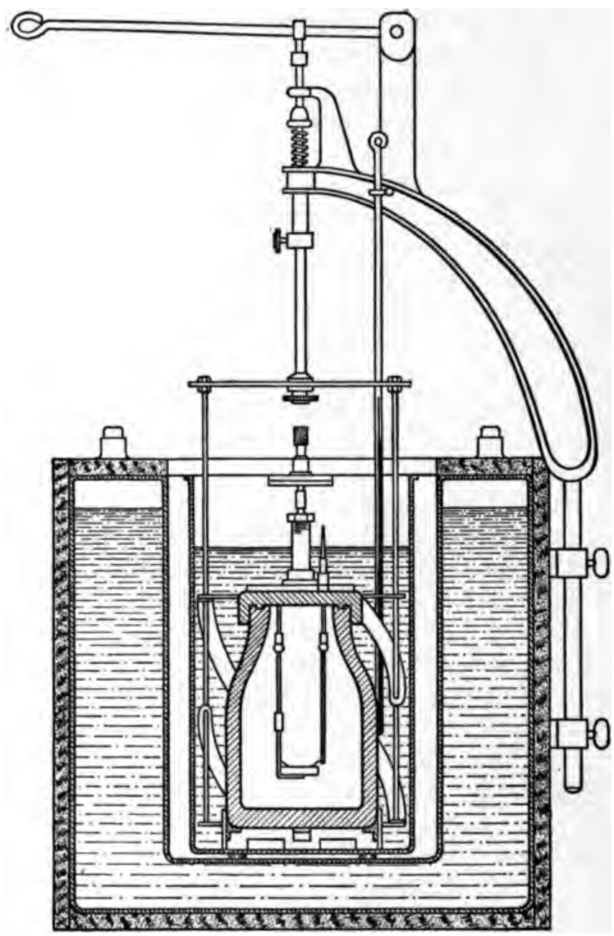

FIG. 38. Mahler bomb calorimeter.

of heat by making its walls double with an air space between, and by covering the outside with a thick layer of felt.

The heating value of a fuel burned in a coal calorimeter may be calculated if the weight of the sample of fuel, the weight of

water, and its rise in temperature is known. The method of doing this is illustrated by the following example: A sample of coal weighing .004 pounds is burned in a coal calorimeter containing 4.41 pounds of water and produces a rise in temperature of 11.2 degrees.

The amount of heat absorbed by the water equals

$$11.2 \times 4.41 = 49.392 \text{ B.T.U.}$$

and this amount of heat was produced by the burning of .004 pounds of coal. Therefore, if one pound of coal had been burned, the heat produced would have been:

$$\frac{49.392}{.004} = 12{,}348 \text{ B.T.U.}$$

which represents the heating value of the coal tested, expressed in heat units per pound of coal, which is the usual way of expressing the heating value of coal.

35. Gas Calorimeter.—The Junker Calorimeter, shown in Fig. 39, is a form of gas calorimeter which is widely used in this country. It consists of three parts: a gas meter for measuring the amount of gas burned, a Bunsen burner by means of which the gas may be burned completely, and the calorimeter proper, for passing the heat developed by the burning gas into water where it may be measured easily.

The calorimeter proper consists of a nickel-plated cylindrical copper or brass shell which has a number of small brass tubes passing through it from one end to the other. The hot gases resulting from the burning of the gas pass to the top of the calorimeter through one set of tubes and to the bottom again through another set, while water circulates around the tubes and absorbs the heat from the gases. The rate at which the hot gases pass through the calorimeter and also the amount of water passing through the calorimeter may be regulated, thus insuring that the gases will be cooled to the temperature of the atmosphere before they leave the calorimeter. The body of the calorimeter is nickel plated to prevent the radiation of heat. It is seen, then, that all of the heat developed by the burning gas will pass into the water and may be measured by weighing the water which passes through the calorimeter in a given time, by measuring the number of cubic feet of gas burned during the same length of time, and by noting the temperature of the water entering and leaving the calorimeter.

7

The method of calculating the heat contained in the gas, or its heating value, may be illustrated by using the following data:

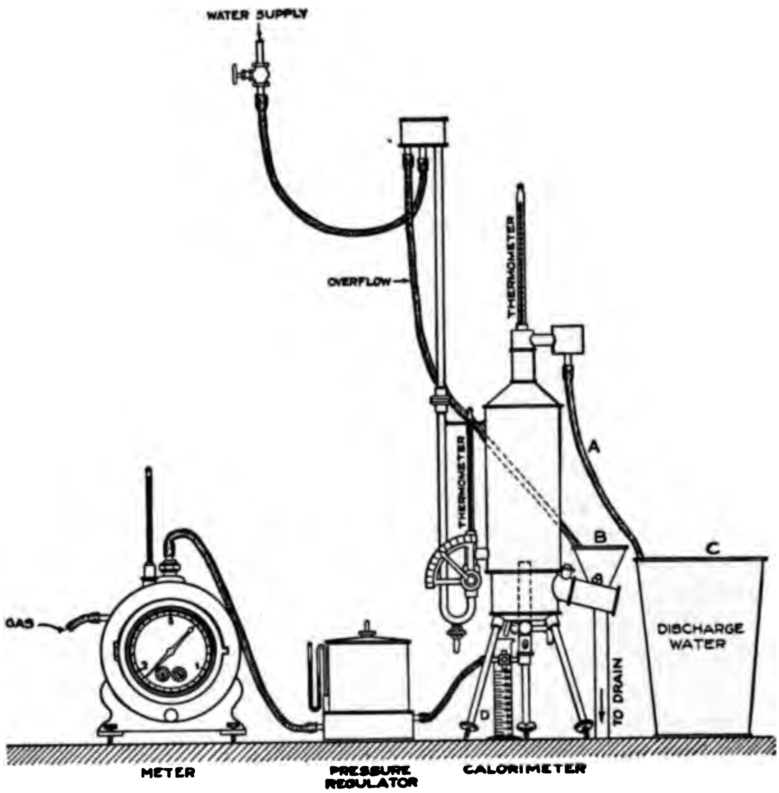

FIG. 39. Junker's gas calorimeter.

Weight of water passing through calorimeter	=5 lb.
Volume of gas burned in same length of time	=.16 cu. ft.
Temperature of water entering calorimeter	=50° F.
Temperature of water leaving calorimeter	=70° F.
Change in temperature of water $=70-50$	=20° F.
The amount of heat absorbed by the water equals 5×20	=100 B.T.U.

and this amount of heat was developed by the burning of .16 cu. ft. of gas. Since the heating value of a gas is usually expressed in B.T.U. per cubic foot, the heating value of this gas is

$$\frac{100}{.16}=625 \text{ B.T.U. per cu. ft.}$$

QUESTIONS

31. Explain why a piece of paper if wrapped tightly around an iron rod and held in a match flame for an instant will not be scorched, but if it is wrapped around a glass rod it will be scorched at once.

32. If the tongue is placed against a frosted piece of iron on a cold winter day it will freeze to the iron almost instantly. If touched to a piece of frosted wood, it will not freeze to it. Explain this.

33. Explain why a thick glass bottle is liable to break when hot water is poured into it, but a thin glass bottle is not liable to break under the same conditions.

34. Explain why dark-colored clothes keep us warmer in winter and light-colored ones keep us cooler in summer.

35. Why is tightly packed wool a better insulator than loose wool?

36. A room 16×30 ft. with a nine-foot ceiling has one of its long and one of its short sides exposed to the outside. The walls are 12 in. thick and built of brick. In the 30 ft. wall there are 4 windows each 3×5 ft. and in the 16 ft. wall there are 2 windows each 3×5 ft. and one wooden door 4×7 ft. Calculate the amount of heat lost through the walls, windows, and door when the outside temperature is 10 degrees below zero and the temperature inside the room is 68° F.

37. A sample of coal weighing $\frac{1}{10}$ ounce is burned in a coal calorimeter and causes the temperature of the water in the calorimeter to rise 5° F. The calorimeter contains 2 gallons of water. How many heat units does one pound of this coal contain? (Use 8.34 pounds as the weight of one gallon of water.)

38. A man wishes to place a coil of 1 inch pipe in his furnace for heating 60 gallons of water per hour from a temperature of 40° F. to a temperature of 180° F. It is assumed that a square foot of pipe surface will transmit 50 B.T.U. per hour for each degree difference of temperature between the interior of the furnace and the water in the coil, and it is also assumed that the difference in temperature in this case is 300° F. What length of pipe should the coil mentioned above contain?

39. Why does the return pipe of a hot water heating system enter the boiler at the bottom?

40. The outside surface of a Junker calorimeter is polished and nickel plated, and the directions for the use of the apparatus say it is very important that the outer surface of the calorimeter should be kept clean and polished. Explain the reason for this.

CHAPTER V

GENERATION OF HEAT

36. Source of Heat.—All of the heat used by man, except that which is derived from some natural source such as the sun, is obtained by changing other forms of energy into heat energy. It has been shown in a previous chapter that mechanical energy may be changed into heat by means of friction. Electrical energy may also be changed into heat. This is done by placing resistance in a circuit through which electricity is flowing. Whenever a current of electricity meets a resistance to its flow, heat is developed. The resistance may be in the form of a wire of low-conducting power, in which case the wire will become heated, or it may be in the form of an air gap across which the current of electricity is forced to flow, in which case the heat is developed in the air gap. The generation of heat by electricity is becoming more important every year. Many street cars are heated by electricity and large quantities of electricity are used in developing heat in electric furnaces where a high temperature is desired. This method of generating heat will be treated more fully in the latter part of this chapter.

37. Combustion of Fuel.—By far the largest part of the heat used by man for commercial and domestic purposes is obtained from the combustion (burning) of fuel. The combustion of fuel is a process by which oxygen unites with certain chemical substances in the fuel, liberating heat. By the combustion of fuel, the chemical energy in the fuel is changed into heat.

The most common fuel is coal. Other fuels of less importance are wood, peat, coke, natural gas, various manufactured gases, and crude oil and its products, such as gasoline and kerosene.

The chemical substances from which nearly all of the heat is liberated in burning fuel are carbon and hydrogen, and the amount of these substances present in the fuel determines the amount of heat that may be obtained from burning it. There are also other substances in fuels, such as nitrogen, oxygen, and water, which pass off as gas when the fuel is burned. The remainder of the fuel is earthy matter or ash.

The oxygen supplied to fuel in order to carry on combustion comes from air, which consists of .207 parts, by volume, of oxygen, and .793 parts of nitrogen. The nitrogen plays no part in the combustion of fuel, but seems to be present only for the purpose of diluting the oxygen. When hydrogen unites with oxygen the amount of heat liberated is 62,000 B.T.U. for each pound of hydrogen which enters the union. The product of this union is water, which consists of two parts, by volume, of hydrogen and one part of oxygen.

When carbon unites with oxygen two products may result, depending upon the proportion of oxygen which unites with the carbon. If one part, by volume, of carbon unites with two parts of oxygen the resulting product is carbon dioxide and the amount of heat liberated is 14,500 B.T.U. for every pound of carbon which enters the union. If one part, by volume, of carbon unites with only one part of oxygen, the resulting product is carbon monoxide and the amount of heat liberated is 4400 B.T.U. for every pound of carbon that enters the union. When carbon dioxide results from the burning of carbon the combustion is *complete,* since oxygen will not unite with carbon in a greater proportion than two parts of oxygen to one of carbon. When carbon monoxide results from the burning of carbon the combustion is *incomplete* because more oxygen might have combined with the carbon, and because the carbon monoxide itself is capable of being burned.

The importance of securing complete combustion of fuel may now be seen. When there is complete combustion 14,500 B.T.U. are obtained for every pound of carbon burned, while if the combustion is incomplete, only 4400 B.T.U. are obtained for every pound of carbon burned. Incomplete combustion, therefore, causes a loss of 10,100 B.T.U. for every pound of carbon burned. Incomplete combustion may be caused by too small a supply of air to the fire, by the carbon not coming in contact with oxygen, or by the carbon and oxygen being cooled below their combining temperature before they have had time to complete the process of combustion.

38. Heating Value of Fuel.—The amount of heat obtained from combustion of one pound of hydrogen is 62,000 B.T.U. while that obtained from a pound of carbon, if combustion is complete, is 14,500 B.T.U. Hence, a fuel which is rich in hydrogen will have a high heat producing value. The liquid fuels,

such as gasoline and kerosene, contain more hydrogen than does coal, and these liquid fuels, therefore, have a higher heat producing value per pound than does coal. All of the ordinary commercial fuels contain a much larger proportion of carbon than of hydrogen, and the larger part of the heat obtained from burning them comes from the carbon rather than from the hydrogen.

When the chemical composition of a fuel is known, its heating value per pound may be calculated approximately by the formula:

$$\text{B.T.U.} = 14{,}500\ C + 62{,}000\left(H - \frac{O}{8}\right)$$

In this formula C, H, and O represent the parts of a pound of carbon, hydrogen, and oxygen which a pound of the fuel contains.

It is assumed that all of the oxygen in the coal is already combined with a part of the hydrogen. As oxygen combines with hydrogen in the ratio of 1:8, a part of the hydrogen equal to one-eighth of the weight of oxygen will not produce heat. The remainder of the hydrogen, or $\left(H - \frac{O}{8}\right)$, will be available for producing heat.

Example:

What is the heat-producing value of a pound of coal which has the following chemical composition: Carbon, 78.31%; Hydrogen, 5.36%; Nitrogen, 1.85%; Oxygen, 8.80%; Ash, 5.68%?

Solution:

In each pound of this coal there are .7831 pounds of carbon, .0536 pounds of hydrogen, and .0880 pounds of oxygen. Therefore the heating value of one pound of this coal is:

$$\begin{aligned}\text{B.T.U.} &= 14{,}500C + 62{,}000\left(H - \frac{O}{8}\right)\\ &= (14{,}500 \times .7831) + 62{,}000\left(.0536 - \frac{.0880}{8}\right)\\ &= 11{,}355 + 62{,}000 \times .0426\\ &= 11{,}355 + 2{,}641\\ &= 13{,}996 \text{ B.T.U.}\end{aligned}$$

Out of the entire 13,996 B.T.U. in a pound of this coal, the carbon supplies 11,355 B.T.U. and the hydrogen supplies only 2641 B.T.U. Although the heating value of hydrogen is much higher than that of carbon, there is a much larger proportion of carbon than of hydrogen in the coal, hence nearly all of the heat is derived from the carbon.

The approximate composition and heating value of some common fuels are given in the following table. The composition of a particular kind of fuel may vary through a wide range, hence the values in this table should

not be taken as fixed quantities but only as the composition and heating value of one sample of each kind of fuel:

Kind of fuel	Carbon %	Hydrogen %	Nitrogen %	Oxygen %	Ash %	B.T.U. per lb.
Anthracite coal.....	85.66	2.78	.77	2.45	8.34	13,955
Semi-bituminous coal.	85.91	4.58	1.07	3.24	5.20	15,045
Bituminous coal....	68.14	5.38	1.34	15.83	9.31	11,988
Lignite............	47.34	5.93	.66	27.53	18.54	8,408
Wood..............	50.0	6.0	1.0	41.0	2.0	7,870
Crude oil..........	82.0	14.8	....	3.2		20,718
Kerosene..........	84.0	16.0	....	....	.....	22,100
Gasoline..........	84.0	16.0	....	....	.....	22,100

39. Air Required for Combustion.—Since air is the usual source of the oxygen used to maintain combustion, there must be a continuous supply of it to the fuel if combustion is to be maintained steadily, and the supply of air must be large enough to contain a sufficient quantity of oxygen to carry on the combustion. Different fuels will require different amounts of air on account of their chemical composition being different. Those fuels containing a large proportion of hydrogen require more air for combustion than those containing a small proportion, because the hydrogen requires more air for combustion than any other substance in the fuel.

The weight of air required to furnish oxygen for one pound of fuel may be calculated by the following formula:

$$A = 34.56\left(\frac{C}{3} + H - \frac{O}{8}\right)$$

in which A = pound. of air required per pound of fuel
C = part of a pound of carbon in one pound of fuel
H = part of a pound of hydrogen in one pound of fuel
O = part of a pound of oxygen in one pound of fuel

Applying this formula to the kind of coal mentioned in the example above in which the carbon was 78.31%, hydrogen 5.36%, nitrogen 1.85%, oxygen 8.8%, and ash 5.68%, will give

$$\begin{aligned} A &= 34.56\left(\frac{C}{3} + H - \frac{O}{8}\right) \\ &= 34.56\left(\frac{.7831}{3} + .0536 - \frac{.088}{8}\right) \\ &= 34.56\ (.261 + .0536 - .011) \\ &= 34.56 \times .3036 \\ &= 10.49 \text{ lb.} \end{aligned}$$

The weight of air given by this formula is the least weight that will supply the oxygen required for complete combustion. As there is a large chance that some of the oxygen will not come in contact with the carbon and hydrogen, it is necessary to supply more air to the fuel than indicated by the above formula. The excess of air to be supplied in any case depends upon the kind of fuel and the conditions under which it is being burned. In general, 1.5 to 2.0 times the amount of air given by the above formula is required for solid fuels, and from 1.25 to 1.75 for liquid fuels. Thus, the coal mentioned above would require about 21 pounds of air to be supplied to the furnace per pound of coal in order to insure complete combustion instead of only 10.49 pounds.

40. Temperature of Combustion.—If the heat liberated by the combustion of fuel is confined in such a way that no radiation can take place, the resulting increase in temperature of the products of combustion may be expressed by the following formula:

$$T=\frac{H}{.217W}$$

in which T = the increase in temperature, degrees F.

H = B.T.U. liberated per pound of combustible material

W = weight of gaseous products in pounds

.217 = the specific heat of the gaseous products

Applying this formula to the sample of coal mentioned in the example above, it will be seen that the per cent. of combustible material is $78.31+5.36+8.8=92.47\%$ and the heat liberated per pound of combustible material amounts to $\frac{13,996}{.9247}=15,136$ B.T.U. The products of combustion contain all of the fuel except the ash and also all of the air supplied to the fire. The products of combustion include, from the fuel

$$78.31+5.36+1.85+8.8=94.32\%$$

and the air supplied per pound of material which enters the products of combustion amounts to

$$\frac{21}{.9432}=22.15 \text{ lb.}$$

The products of combustion will then contain one pound of combustible material for every 22.15 lb. of air, or the products of combustion resulting from burning one pound of combustible material will weigh $.94+22.15=23.09$ lb.

The increase in temperature resulting from the combustion will therefore amount to

$$
\begin{aligned}
T &= \frac{H}{.217\ W} \\
&= \frac{15136}{.217 \times 23.09} \\
&= \frac{15136}{5.01} \\
&= 3021^\circ \text{ F.}
\end{aligned}
$$

The actual temperature realized would be somewhat less than this on account of certain losses occurring in the furnace which cannot be avoided. The necessity for reducing the excess of air supplied to the fuel to as small an amount as possible is indicated by the above example, since any excess air requires heat to raise its temperature and therefore reduces the maximum temperature attained.

The generation of heat at high temperatures is necessary, not only in order to secure good combustion of coal, but also in many cases on account of the use made of the heat after it is generated. Many processes, regardless of the kind of fuel used, require heat of very high temperature, such, for example, as in melting various metals, smelting ores, welding, and in the manufacture of certain substances such as aluminum, carborundum, carbide, etc. In all cases where a high temperature is required the heat must be generated at the point where it is used, because it is impossible to store or transport heat at very high temperatures.

41. Blow-pipe Welding.—When two pieces of metal are to be welded, the surfaces that are to be joined are first brought to a high temperature. The welding may then be completed by pressing or hammering the two surfaces together, or they may be simply brought together without pressure if the metal is in a molten condition; the surfaces will then fuse and run together. In either case a very high temperature is required. If the pieces of metal to be welded are large, it is difficult to heat the welding surfaces to a high temperature because the heat is rapidly conducted away from the surfaces through the body of the metal.

One of the methods of producing welding temperature in metals is by directing the flame from a blow-pipe or torch against the parts to be heated. The flame from a blow-pipe is intensely hot and, at the same time, is small and may be directed upon the

point where the heat is most needed. Blow-pipe flames for welding are made by burning with pure oxygen a gas having a high heating value.

The high temperatures obtained with a blow-pipe are due partly to the use of a gas having a high heating value which gives a large amount of heat in a small flame, and also to the use of pure oxygen instead of air. If air were used the large proportion of nitrogen in it would dilute the products of combustion and it would have to be heated to the flame temperature, thus absorbing and carrying away part of the heat and preventing the flame temperature from being as high as would result from the use of pure oxygen. The oxygen and the other gas are stored in tanks under pressure in order to store a large amount in a small space and also to furnish pressure for blowing the flame against the part to be heated.

The gases most commonly used in blow-pipe welding are oxygen and hydrogen, and oxygen and acetylene. These systems are called respectively the oxy-hydrogen process and the oxy-acetylene process.

In the oxy-hydrogen process, hydrogen is burned in pure oxygen, the products of this combustion being water, or water vapor. Two volumes of hydrogen unite with one volume of oxygen in burning; hence the oxy-hydrogen blow-pipe uses approximately one-half as much oxygen, by volume, as of hydrogen, the ratio being a little less than one-half in practice because some air is drawn into the blow-pipe flame.

Hydrogen has a heating value of about 62,000 B.T.U. per pound or 346 B.T.U. per cubic foot, and, as this amount of heat is developed within the small space of the blow-pipe flame, it gives a high temperature. The temperature of the flame is about 4000° F., which is sufficiently high for welding a great variety of objects. Metals may also be cut readily by the oxy-hydrogen flame, and it is often employed for this purpose. The flame is particularly suitable for cutting because it is thin and long, which permits it to reach through a comparatively thick piece of metal. Steel bars up to 24 inches thick may be cut readily by the oxy-hydrogen flame. In cutting metals the flame melts out a thin slice from the metal, leaving a clean, sharp cut.

The apparatus for oxy-hydrogen welding and cutting consists of two cylinders, as shown in Fig. 40, which contain the compressed oxygen and hydrogen under a high pressure, and fitted

with valves for reducing the pressure to the proper amount, and gages for registering the pressure. The oxygen and hydrogen are led by separate pipes to the torch, where the two gases are mixed. There is no danger of the flame flashing backward into the oxy-hydrogen torch because the velocity of the gases leaving the torch is great enough to prevent the flame travelling backward.

In the oxy-acetylene blow-pipe, acetylene gas is burned in pure oxygen. Acetylene is a gas composed of hydrogen and carbon and has a heating value of 21,421 B.T.U. per pound, which is a lower heating value than that of hydrogen; but, on account of its greater density, acetylene has a heating value of

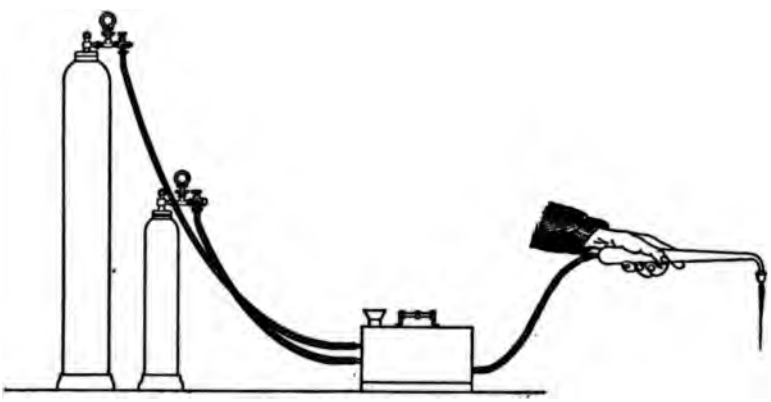

FIG. 40. Oxy-hydrogen blow-pipe.

1554 B.T.U. per cubic foot. The combustion in an acetylene blow flame takes place in two stages: first, there is an inner pencil of flame in which the acetylene burns to carbon monoxide and water vapor; and, second, there is an outer envelope in which the carbon monoxide burns to carbon dioxide and also some acetylene burns to carbon dioxide and water vapor. The tip of the inner pencil of flame has the highest temperature, which is about 6500° F., but the larger quantity of heat is contained in the outer envelope on account of its larger size. In welding or cutting metals the tip of the inner pencil of flame is brought in contact with the surface to be heated. The outer envelope then forms a protection for the point of highest temperature and also serves to pre-heat the metal and reduce strains in it due to expansion and contraction. The outer envelope of flame also

prevents oxidation of the metal that is being melted. The flame of the oxy-acetylene blow-pipe is shorter than that of the oxy-hydrogen blow-pipe; hence it is not so well adapted to cutting thick pieces of iron or steel.

The oxy-acetylene welding and cutting apparatus resembles the oxy-hydrogen apparatus in that it has two tanks, one for oxygen and one for acetylene, but the acetylene is not stored under high presure as is hydrogen, because it is explosive at high pressures.

The form of torch for acetylene, shown in Fig. 41, is somewhat different from that for hydrogen. Acetylene is liable to flash back, hence a great many of the torches keep the oxygen and

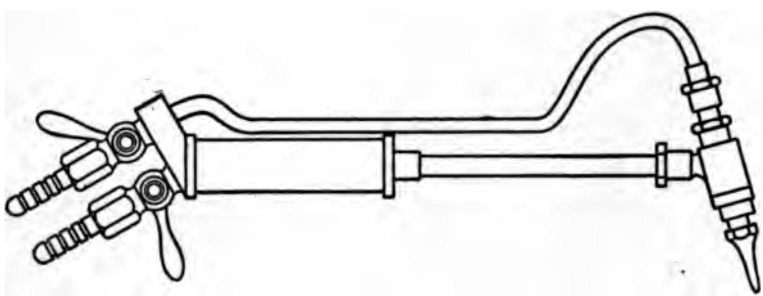

FIG. 41. Oxy-acetylene blow-pipe.

acetylene separate up to the tip of the torch; other torches have some porous substance in them to divide the acetylene into small streams which prevent the flame from travelling backward.

42. Thermit Welding.—A process of welding has been developed within recent years which resembles casting, in that melted metal is poured into a mold surrounding the metal that is to be welded. In this process the metal for making the weld and also the heat for melting the metal are obtained by chemical actions in a substance called *thermit,* from which this kind of welding takes its name.

Thermit is composed of iron oxide and finely powdered aluminum. This substance is capable of burning, and in doing so the iron oxide, which is composed of iron and oxygen, is decomposed, the oxygen leaving the iron and uniting with the aluminum, forming aluminum oxide. These chemical changes generate large quantities of heat and raise the temperature of the thermit to about 5400° F. The thermit is melted by the large

quantity of heat evolved and the aluminum oxide, being lighter collects on top of the molten mass, leaving the pure iron at the bottom.

In making a weld, a mold is first made around the parts to be joined, with holes properly placed for pouring the metal. A sufficient quantity of thermit is then placed in a crucible having an opening at the bottom which is stopped temporarily with clay. The thermit is then ignited and when the chemical actions described above have proceeded far enough to melt the iron, the opening in the bottom of the crucible is tapped and the melted

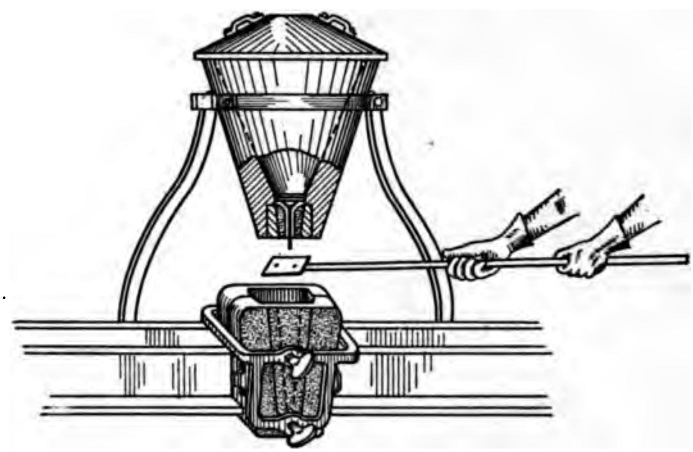

FIG. 42. Thermit welding.

iron runs into the mold. An apparatus of this kind is shown in Fig. 42.

Two distinct methods are followed in applying thermit welding. One of these utilizes the heat developed by the chemical changes taking place in the thermit to bring the pieces which are to be joined to a welding temperature, when they are forced together by suitable clamps and butt-welded in a manner similar to forge welding. In the other method the ends of the pieces to be joined are fused or melted together by the molten metal resulting from the chemical actions in the thermit, the molten metal being held by a suitable mold surrounding the joint. When the fused parts cool they form one solid piece.

The first method of welding is usually applied to pipes, tubes, and small rods. In making a weld by this method the ends to be

joined are first filed or machined to fit closely together, after which they are held together by clamps and surrounded with a cast iron mold of such size as to hold just enough thermit to bring the parts to a welding heat. The necessary amount of thermit is then ignited in a flat bottom crucible and as soon as the thermit is melted it is poured into the mold. The aluminum oxide, being light, collects at the top of the crucible and is poured into the mold first where it adheres to the mold and pieces to be welded and prevents the melted iron which follows from sticking to them. As soon as the molten mass has been in the mold long enough to bring the pieces to a welding temperature, they are forced together by the clamps and the weld completed.

Rods up to 2 inches in diameter and pipe from 1 to 6 inches have been welded by this method. Its chief application is in welding ammonia, compressed air, high-pressure steam and hydraulic pipe lines, where the work has to be done in place.

In the second method of thermit welding the ends to be joined are not brought close together, but a space is left between them varying from ½ to 2 inches wide, depending upon the size of the parts to be welded. After the parts to be welded are thoroughly cleansed of grease, dust, etc., they are surrounded by a mold which is provided with pouring gates and risers and which also has an opening at the bottom through which heat may be applied to pre-heat the parts to be joined. When the space between the parts to be joined is of uniform cross-section, a wooden pattern is made of the size and shape of the opening. This is placed in the opening so that, after the mold is made and the pattern removed, there will be a hollow space in it of the same shape and size as the space between the parts to be joined. Where this space has an irregular cross-section it is filled with wax while the mold is being made. Heat is then applied to the bottom opening of the mold and the wax is melted and runs out. The heating is then continued until the pieces of metal to be welded are red hot, when the melted thermit is run into the mold through an opening in the bottom of the crucible.

In making welds by the second method best results are obtained if the metal run into the mold has the same composition as the parts to be joined. This result is accomplished by adding the necessary substances to the thermit, such as nickel, when nickel steel is to be welded, manganese or chromium in welding manganese steel or chrome steel, etc.

This method of welding has its chief application in welding street railway rails and in repairing all kinds of machinery where the sections to be welded are large and where the work must be done rapidly and in place. Among such repairs may be mentioned the welding of engine frames, crank shafts, fly-wheels, and large castings of every description.

43. Electric Welding.—An electric current may be employed for welding by two methods, known as resistance welding and arc welding. Resistance welding depends upon the fact that if a resistance is placed in an electric current heat will be developed in the resistance. In this method of welding the parts to be welded are placed in the electric circuit so the current must flow through them. The ends of those parts where the weld is to be made are brought together so the electric current will flow from one to the other, but the contact of these pieces offers more resistance to the electric current than the solid metal, hence the pieces are heated at the point of contact. As soon as the pieces of metal to be welded reach a welding temperature they are pressed together, making a butt weld.

The resistance method of welding has the advantage that the heat is developed in the metal itself at the joint and the current is therefore used economically. In other systems the heat is not generated within the metal; hence, some of it is dissipated and wasted. Other advantages of this system of welding are that the metal in the joint is the same as elsewhere; the metal can be held at any temperature for any desired length of time and the heat increased or decreased at will; the joint is in plain view while the weld is being made; and the process does not produce smoke, dirt, or heat; hence, the apparatus may be located anywhere.

Various forms of machines are built for resistance welding but they are alike in that they have a transformer which is provided with insulated clamps for holding the pieces of metal to be welded and with a means for pressing the pieces together. Some machines are also provided with means for shaping the weld after it is made, such as for removing fins or for preventing the joint from bulging. The machines are built in various sizes and types to suit the kind of work on which they are to be employed and the size of metal to be welded.

The sizes of metal that may be welded by this method vary from the smallest size up to sections of 3 square inches. Among

the common applications of this process of welding is the welding of metal tires of all kinds and other parts in the running gear of wagons and carriages, bicycle parts, parts of tools, wire of all kinds for such purposes as hoops, fencing, etc., pipe chains, automobile parts and the like. The output of machines varies with the size and shape of the sections to be welded. Bars $\frac{3}{4}$ inch in diameter may be welded in 6 seconds and some butt-welding machines make 20 welds per minute. Spot and point welders are made to operate automatically and make from 5 to 10 welds at one time.

Electric arc welding depends upon the fact that if two electric conductors are brought together and then separated a short distance an arc or flame will be formed in the air space between them, and the electric current will continue to flow through the arc and maintain it. Electrical energy is changed into heat in the arc, and as this heat is developed within a small space the resulting temperature is very high.

There are three processes of arc welding, called, after the names of the inventors, the Bernardos process, the Slavianoff process, and the Zerener process. In the Bernardos process the arc is drawn between the work to be welded, which forms one terminal, and a carbon electrode, which forms the other terminal. The Slavianoff is the same as the Bernardos, except that a metal electrode is used instead of a carbon one. In the Zerener process the arc is drawn between two carbon electrodes and the arc is blown against the work to be welded by means of a magnet. The Zerener process has never come into extensive use and is therefore of little importance.

A diagrammatic illustration of the apparatus used in the Bernardos process and its arrangement is shown in Fig. 43. This consists of an electric generator or other source of direct current electricity, a switch and circuit breaker, two water rheostats for controlling the strength of current, and a metal welding table to which one wire is connected, thus making the table a part of the electric circuit. The other electrode consists of a carbon rod $\frac{3}{4}$ or 1 inch in diameter and about 6 inches long which is held in a metal holder having a wooden handle. The pieces to be welded are placed on the metal table, with which they make electrical contact, the rheostats are adjusted for the proper strength of current, and the carbon electrode is brought in contact with the metal to be welded and then drawn away about

¾ of an inch in order to establish the arc. The heat from the arc soon melts the metal and causes it to run together. In case additional metal is to be run into the weld it is done by holding a bar of the metal in the arc, which melts it. After the weld is made and while it is still hot it is usually necessary to hammer it to avoid sponginess.

The Bernardos process of welding is liable to make a hard weld on account of carbon from the electrode mixing with the iron. The Slavianoff process overcomes this by using as an electrode a bar of metal having the same composition as the pieces to be welded, and it therefore gives a stronger weld; but, on the other hand, the metal electrode gives a shorter arc which is more difficult to manipulate.

Electric arc welding has to be done in a separate enclosure as the bright light from the arc would interfere with workmen at

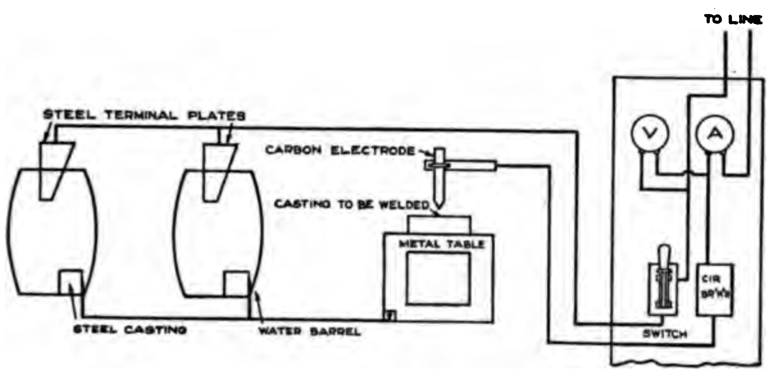

FIG. 43. Electric welding apparatus.

other occupations. As the rays of light from the arc irritate the skin, the operator has to protect his face with a mask and his hands with gloves.

An electric furnace operates on the same principles as the electric welding. Large carbon rods are used for the electrodes and an arc established between them. The space between the electrodes where the arc is formed is surrounded by fire-brick or other refractory substances to confine the heat and maintain a high temperature. The substances to be melted are packed between the carbon electrodes where they will be subjected to the intense heat of the arc. The electric furnace is used in the

manufacture of various substances which require an extremely high temperature for their formation. Examples of these are carborundum, used as an abrasive, which is made by fusing charcoal and sand; calcium carbide, used for making acetylene gas, made by fusing lime and coke; and aluminum, made by fusing certain kinds of clay.

QUESTIONS

41. What is meant by the *combustion* of a fuel?

42. What are the substances in fuel which generate the most heat, and how do these substances generate heat?

43. Why is it important to secure *complete* combustion of fuel?

44. What conditions are necessary in order to secure complete combustion of fuels?

45. The analysis of a certain kind of coal showed it to contain: Carbon, 74.33%; Hydrogen, 4.96%; Nitrogen, 1.43%; Oxygen, 7.61%. What is the heating value of a pound of this coal?

46. If only one-half of the carbon in the above coal were burned completely, the other half being burned incompletely (so as to form carbon monoxide) how much heat would be obtained from one pound of the coal?

47. How much air is required to completely burn one pound of the above coal? About how much air would be supplied to the furnace in actual practice?

48. What is the theoretical temperature of combustion for the above coal?

49. What is *Thermit?*

50. Describe the process of thermit welding.

51. Why does the oxy-hydrogen blow-pipe give a very high temperature?

52. Why does the oxy-acetylene blow-pipe produce a hotter flame than the oxy-hydrogen blow-pipe?

53. What are the advantages of electric welding?

CHAPTER VI

MEASUREMENT OF PRESSURE AND EFFECT OF HEAT ON GASES

44. Pressure.—The word pressure has two different meanings. It is used to refer to the total force produced by the weight of a substance, or it may refer to the force exerted upon a unit of area. Fig. 44 shows a glass vessel of square cross-section filled with water to a height of 2 feet. Since the area of the bottom of the vessel is one square foot, the vessel contains 2 cubic feet of water and, as a cubic foot of water weighs 62.4 pounds, the pressure exerted upon the bottom of the vessel amounts to $2 \times 62.4 = 124.8$ pounds. This pressure is usually spoken of as the *total pressure*, and it is measured in *pounds*. The pressure exerted upon each square inch of the bottom of the vessel will be $\frac{124.8}{144} = .866$ pounds. This pressure is called *unit pressure*, since it is the pressure exerted upon a unit of area, but it is usually referred to simply as pressure, and is measured in pounds per square inch. Thus, in the above example the pressure upon the bottom of the vessel is .866 pounds per square inch. The pressure exerted by a column of water is proportional to the height of the column. If the depth of water in the above vessel had been one foot instead of two, the pressure exerted upon the bottom would have been .433 pounds per square inch. Each foot height of water column adds .433 pounds per square inch to the pressure exerted

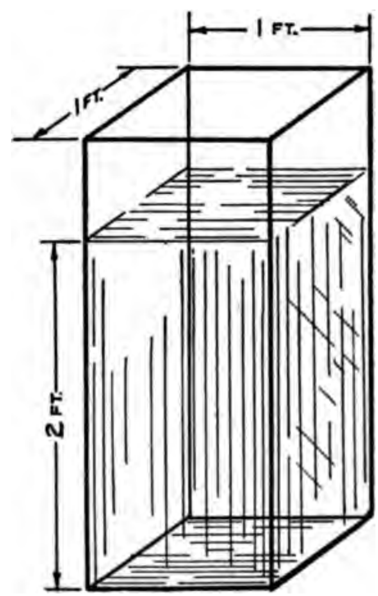

FIG. 44.

upon the bottom of the vessel. A depth of three feet of water in the above vessel would exert a pressure of

$$3\times.433=1.299 \text{ lbs. per sq. in.}$$

upon the bottom of the vessel. One foot of water column exerts a pressure of .433 lb. per sq. in.; therefore to exert a pressure of one pound per square inch would require a column having a height of

$$\frac{1}{.433}=2.31 \text{ ft.}$$

45. Atmospheric Pressure.—The earth is surrounded by a layer of air which is estimated to be about fifty miles thick. This air exerts a pressure, due to its weight, upon all objects

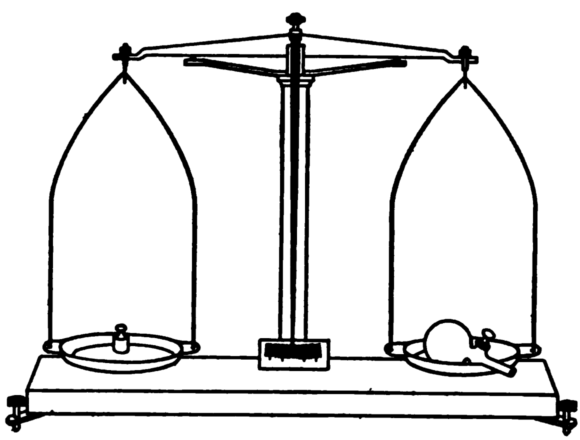

FIG. 45. Weighing air.

with which it comes in contact. At sea level the pressure of the atmosphere amounts to about 14.7 pounds per square inch, but this varies with the amount of moisture in the air, since moist air is lighter than dry air.

It may not have occurred to some that the atmosphere has weight, but that it has considerable weight may be shown by the following experiment. The glass globe shown in Fig. 45 is attached to an air pump and as much air pumped out of it as possible, after which the valve on it is closed and it is detached from the air pump. The globe, which now contains practically no air, is placed on the scales and its weight noted. Next,

the valve on the globe is opened and air is allowed to enter. If the globe is weighed now it will be found to weigh considerably more than before, showing conclusively that the air has weight. In fact, it takes only about 13 cubic feet of air to weigh a pound. On this basis, the air contained in a large room would weigh more than a man could lift.

The pressure of the atmosphere varies with the elevation above sea level. If the atmospheric pressure is measured at a point 10,000 feet above sea level, it will be found to be only about 10 pounds per square inch. The atmospheric pressure does not vary in exact proportion to the elevation or height of the column of air over the point at which the pressure is measured. In this respect it is different from the pressure produced by a column of water. The reason for this is that water is practically incompressible, while air is not. Each cubic foot of water in a column weighs practically the same, but in an air column the air at the bottom is compressed by that above, causing a given weight of it to occupy less space or to be more dense. In this way the air weighs less and less per cubic foot as the top of the column is approached, so the pressure of the air does not vary exactly with the height or elevation. Various elevations and the corresponding atmospheric pressures are shown in the following table:

Elevations	Atmospheric pressure lb. per sq. in.
Sea level	14.7
1,320 ft.	14.02
2,640 ft.	13.33
3,960 ft.	12.66
5,280 ft.	12.02
6,600 ft.	11.42
7,920 ft.	10.88
10,560 ft.	9.88

46. Vacuum.—A vacuum is a space in which there is no pressure, but the word is also commonly used to designate any pressure below that of the atmosphere or to designate the space in which such low pressure exists. It is impossible to produce a perfect vacuum, but the pressure in a closed vessel may be reduced to a point closely approaching a perfect vacuum. The inside of an incandescent electric globe is almost a perfect vacuum, the

pressure being only about .000015 lb. per sq. in.; but this is a higher degree of vacuum than is usually carried in engineering work. In such work pressures below .9 lb. per sq. in. are rarely used.

In engineering work, vacuum is produced by means of an air pump which pumps the air from the space in which it is desired to maintain a vacuum. One form of air pump is shown in Fig. 46. It consists of a cylinder and piston, so designed that when the piston is at the end of its stroke there will be very little space between the piston and the cylinder head, or clearance space. A large clearance space here would greatly reduce the capacity of the pump, as the air contained in this space must first expand before any more air can be taken into the cylinder.

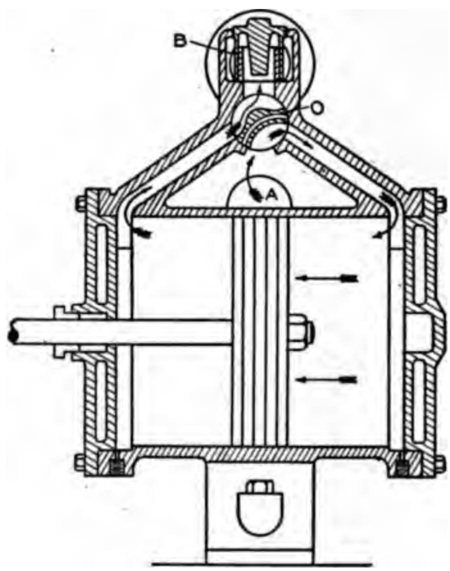

FIG. 46. Air pump.

On the forward stroke of the piston a partial vacuum is produced behind it. Air from the space in which the vacuum is to be maintained then flows into the cylinder, and, upon the return of the piston, is compressed to atmospheric pressure and discharged through the spring controlled valve, *B*. At the end of the discharge stroke, the clearance space is filled with air at atmospheric pressure. In order to increase the capacity of the pump, the clearance space is connected for an instant with the other side of the piston through the valve *O*, thus reducing the

pressure in the clearance space to that which exists on the other side of the piston.

47. The Barometer.—The pressure of the atmosphere may be measured by an instrument called a barometer. A simple form of barometer may be made with a glass tube about 35 inches long closed at one end and filled with mercury. The finger is held over the open end of the tube to prevent the mercury from spilling and the open end of the tube is then placed in a bowl of mercury, as shown in Fig. 47, and the finger removed from the end of the tube. The mercury in the tube will then stand at a height h above the mercury in the bowl. The space B in the top of the tube over the mercury is almost a perfect vacuum, while full atmospheric pressure acts upon the surface of the mercury in the bowl; therefore the height h of the mercury in the tube will represent the pressure of the atmosphere. Since mercury weighs .4908 pound per cubic inch, a pressure of 14.7 pounds

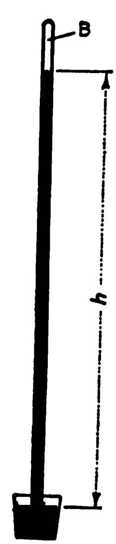

Fig. 47.

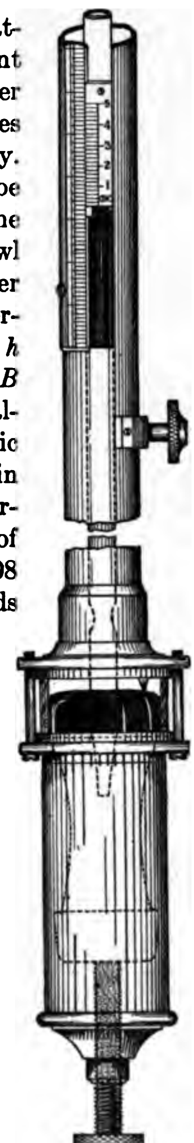

Fig. 48. U. S. Weather Bureau barometer.

per square inch will support a column of mercury $14.7 \div .4908 = 29.95$ inches high. This, therefore, is the height h at which the mercury will stand in the tube shown in Fig. 47 if the atmospheric pressure is 14.7 pounds per square inch. In round numbers the weight of a cubic inch of mercury may be taken as .49 and the height of mercury corresponding to 14.7 pounds per square inch as 30 inches. If the mercury tube shown in Fig. 47 were placed on a mountain 10,000 feet above sea level, the mercury would stand at a height of 20.49 inches, showing that the atmospheric pressure is $20.49 \times .49 = 10.04$ lb. per sq. in.

The simple form of barometer, shown in Fig. 47, is not suitable for accurate measurements because of the difficulty in measuring the distance between the level of mercury in the cup and in the tube. The barometer shown in Fig. 48, which is a Standard U. S. Weather Bureau barometer, may be read very accurately, and is, therefore, suitable for refined measurements. In this barometer the height of the mercury in the cup may be adjusted so that its surface just touches a stationary needle point on the cup. This permits the surface of the mercury being brought always to the same height when the barometer is read. The top of the mercury column is fitted with an adjustable device which may be brought accurately into line with the surface of the mercury in the tube and which permits the height of the mercury column being read to one-ten thousandth of an inch.

In the device shown in Fig. 47, the height h of the mercury column represents the difference in pressure between the closed end of the tube and that of the outside air. An apparatus constructed on this principle and illustrated in Fig. 49 is sometimes used to indicate the amount of vacuum in a closed space. In this device, a glass tube about 80 inches long, with both ends open, is bent into a U-shape, and is filled about half full of mercury. One branch of the glass U-tube is connected to the space in which the vacuum is to be measured, the other branch being left open to the atmosphere. As the pressure is reduced in one branch, the mercury will rise in that branch to a height A, corresponding to the difference in pressure on the surfaces of the mercury in the two tubes. The amount of the vacuum is usually expressed in inches of mercury or simple "inches," which is the difference in height of the two branches of the U-tube. Thus if the height A in Fig. 49, is 20 inches, the vacuum amounts to 20 inches of mercury, or is said to be "20 inches." It should be remembered

that the height of the mercury column indicates the *reduction of pressure*, and not the *actual pressure existing in the space to which the mercury column or gage is attached.* A vacuum of 20 inches means that the pressure has been *reduced* enough to support a column of mercury 20 inches high. Since a column of mercury 1 inch high is equivalent to a pressure of .49 pounds per sq. in., 20 inches of vacuum corresponds to a *reduction* of pressure of $20 \times .49 = 9.8$ lbs. per sq. in. below atmospheric pressure. Before the pressure still existing in the space can be found,

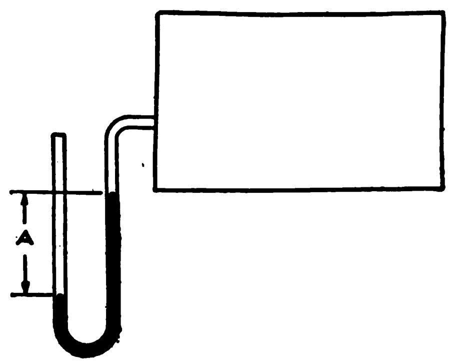

FIG. 49.

it is necessary to know the pressure of the atmosphere. If the atmospheric pressure is 14.7 lb. per sq. in., a vacuum of 20 inches leaves a pressure of $14.7 - 9.8 = 4.9$ lb. per sq. in. If the barometer, which measures the atmospheric pressure, reads 28 inches, then 20 inches of vacuum leaves a pressure of $28 - 20 = 8$ inches of mercury, or $8 \times .49 = 3.92$ lb. per sq. in.

It is seen from the above discussion that a statement to the effect that the vacuum carried by an apparatus is a certain number of inches does not always mean the same thing. Thus, a vacuum of 22.5 inches at a place 5280 feet above sea level is as near a perfect vacuum as 28 inches at New York, which is at sea level. In the first mentioned place 24.5 inches would be a perfect vacuum, while at sea level 30 inches would be a perfect vacuum.

48. Pressure Gages.—An ordinary form of gage for measuring pressures is shown in Fig. 50. This form of gage, which is called a Bourdon gage, contains a tube of oval cross-section bent into the arc of a circle. One end of the tube is fastened to the case

of the gage and the other end is free to move but is attached through small gears to a hand which moves over a dial in such manner that an outward movement of the end of the tube causes the hand to move over the dial in a clockwise direction. The free end of the tube is caused to move by the pressure inside it. Pressure applied to the inside of a tube of oval cross-section tends to make its cross-section round, but, if the oval tube is bent into the arc of a circle, its cross-section cannot become round until the tube is straightened; hence, pressure applied to

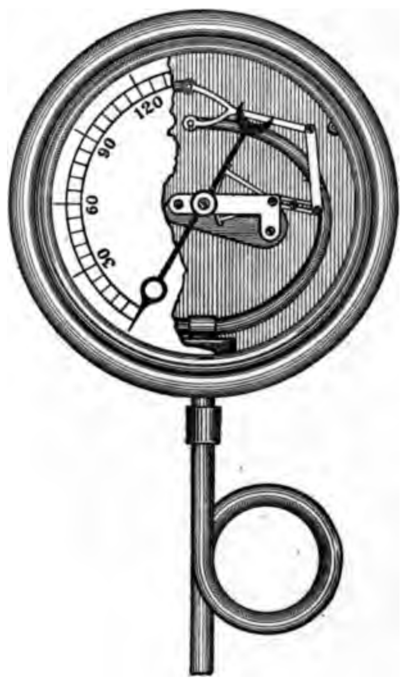

Fig. 50. Pressure gage.

the inside of the oval tube in a pressure gage causes its free end to move outward, and this causes the hand to move over the dial of the gage. In the same way, a reduction of pressure inside the tube causes its free end to move in the opposite direction, or inward.

49. Gage and Absolute Pressures.—Since, in a pressure gage, the pressure of the atmosphere acts upon the outside of the tube, while the pressure to be measured acts upon the inside, the gage

registers pressures above that of the atmosphere. Hence this pressure above atmosphere is called "gage pressure." The true way to measure pressure is from an entire absence of pressure, or absolute zero of pressure. Pressure measured above the absolute zero of pressure, or above a perfect vacuum, is called *absolute pressure.* In engineering work two kinds of pressure are used, namely, gage pressure, which is the pressure indicated on an ordinary pressure gage, and absolute pressure, which is the pressure measured above a perfect vacuum. Usually when a pressure is given without stating whether it is gage or absolute pressure, it is understood to be gage pressure.

To change gage pressure into absolute pressure, add the pressure of the atmosphere to the gage pressure; conversely, *to change from absolute to gage pressure subtract the pressure of the atmosphere from the absolute pressure.* Since the pressure of the atmosphere is not the same at all places, a certain number of pounds per square inch, gage pressure, does not always mean the same absolute pressure. If the atmospheric pressure is not known, it is usually taken as 14.7 lb. per sq. in.

Examples:

1. What is the absolute pressure corresponding to 120 lb. per sq. in. gage pressure?

Solution:

$120+14.7=134.7$ lb. per sq. in. absolute pressure.

2. Find the gage pressure corresponding to 150 lb. per sq. in. absolute pressure.

Solution:

$150-14.7=135.3$ lb. per sq. in. gage pressure.

3. At a certain place the barometer reads 27.5 inches of mercury and a steam gage on a boiler reads 90 lb. per sq. in. What is the absolute pressure of the steam in the boiler?

Solution:

The pressure of the atmosphere is $27.5\times.49=13.475$ lb. per sq. in. The absolute pressure of the steam in the boiler is therefore $90+13.475=103.475$ lb. per sq. in.

50. Vacuum Gages.—Besides the U-tube mercury gage previously described, which may be used to measure either vacuum or a small pressure, other vacuum gages are made which are similar in construction to the Bourdon pressure gage described above, differing only in the manner of connecting the indicating hand to the end of the oval tube. It is desirable that the hand on a vacuum gage move in a clockwise direction, as with a pressure gage, but, as the hand is moved by a decrease in

pressure, which moves the end of the oval tube inward, the connection between the hand and the tube is the reverse of that used in a pressure gage.

The dials of vacuum gages are usually marked to read in inches of mercury, although they may be obtained marked to read in pounds per square inch. It should be remembered that a vacuum gage indicates the *reduction* below atmospheric pressure, in the space to which it is attached, and does not indicate the absolute pressure existing in this space.

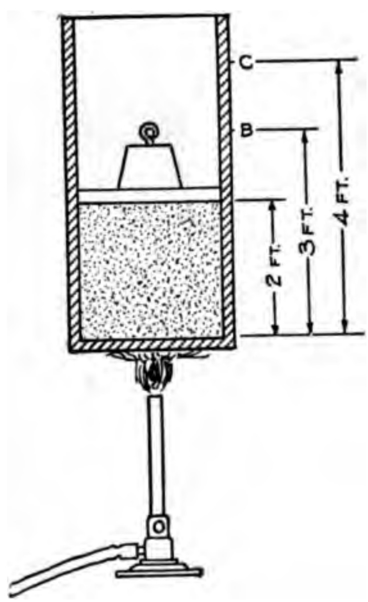

FIG. 51.

Combined gages may also be obtained which indicate either pressure or a vacuum. Such gages usually have zero, which indicates atmospheric pressure, marked at the top of the dial, pressures in pounds per square inch marked to the right of this, and vacuum in inches of mercury marked to the left. Such gages are constructed exactly like pressure gages, except that the zero point is placed further around on the scale.

51. Heating at Constant Pressure.—It has been shown in previous chapters that the effect of applying heat to solids and liquids, is, in general, an expansion of these substances, and that the effect of taking heat away from them is a contraction.

When gases are heated, the effects will depend upon whether the pressure of the gas is kept constant or whether the volume is kept constant. These two cases are considered separately, since the effects produced by heating are different. For studying the effects of heating a gas at constant pressure, we may imagine that the cylinder shown in Fig. 51 contains 2 cubic feet of air and that the temperature of the gas is 32° F. The cylinder has a tightly fitting piston, the area of which is one square foot. Under these conditions the weight upon the gas is constant and therefore it is under a constant pressure.

If heat is applied to the air in the cylinder, its temperature will rise and the gas will expand, pushing the piston upward. By measuring the temperature of the air and its volume as it expands, it will be found that when the temperature has reached 278° F., the piston will be at the position *B*, and the volume of the air will have increased from 2 cu. ft. to 3 cu. ft. If the heating is continued until the temperature of the air is 524° F. the piston will be in the position *C*, and the volume of the air will be 4 cu. ft.

If we tabulate the above results, showing the volume of the air and its temperature, both on the Fahrenheit scale and on the absolute scale, we will have the following:

Volume of air cu. ft.	Fahrenheit temperature	Absolute temperature
2	32	492
3	278	738
4	524	984

From this table it will be seen that the volume has increased in proportion to the absolute temperature, because

$$\frac{2}{3}=\frac{492}{738}$$

and also

$$\frac{2}{4}=\frac{492}{984}$$

It should be noted that the volume is in proportion to the *absolute temperature* and not to the Fahrenheit temperature. This is to be expected, since the absolute scale of temperature starts at the real zero, while the Fahrenheit scale starts at an arbitrary point.

Experiment shows that, *under constant pressure, the volume of a gas varies directly as the absolute temperature* for all ordinary temperatures and pressures. This law holds true for any gas which is not near the temperature at which it changes into a liquid.

Since a gas expands when it is heated, a given volume, for example, a cubic foot of gas, weighs less when it is warm than when it is cold. Hence, heating a gas causes it to rise and it is for this reason that the warmest air in a room is found near the ceiling. It is for this reason, also, that heating a gas causes convection currents in it, since the heated gas rises, while the colder gas sinks to the bottom. The fact that a gas expands when it

is heated accounts for the "draft" in a chimney. The hot gases leaving the fire in a stove or furnace fill the chimney and this column of heated gases is lighter than that outside the chimney; hence, it rises, and in so doing draws other and colder air into the furnace.

52. Heating at Constant Volume.—If, instead of the piston being free to move as in Fig. 51, the cylinder were arranged as shown in Fig. 52, with the piston stationary, the volume of air would remain constant. If the air is heated under these conditions, its pressure will increase as its temperature rises. Starting with the same temperature and volume of gas as before, viz., 2 cu. ft. at a temperature of 32° F., and assuming that the air is under atmospheric pressure, or 14.7 lb. per sq. in., absolute, at the beginning, observe how the pressure increases with the absolute temperature. Before the air is heated its absolute temperature is 32° F., or 492° absolute, and its pressure 14.7 lb. per sq. in. When its temperature has been raised to 278° F. or 738° absolute, its pressure will be 22.05 lb. per sq. in. and, when its temperature has been increased to 524° F. or 984° absolute, its pressure will be 29.4 lb. per sq. in.

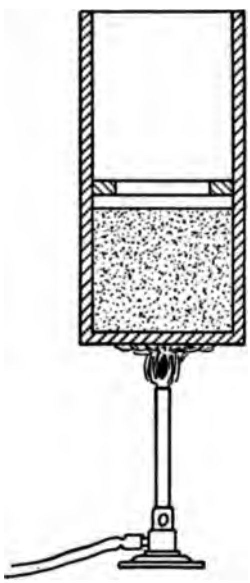

Fig. 52.

Tabulating these temperatures and pressures as in the case of heating under constant pressure will show the following results:

Temperature degrees, Fahr.	Temperature degrees, absolute	Pressure lb. per sq. in.
32	492	14.70
278	738	22.05
524	984	29.40

These results show that the pressure of the gas has increased in direct proportion to its absolute temperature, for:

$$\frac{492}{738}=\frac{14.7}{22.05}$$

and

$$\frac{492}{984}=\frac{14.7}{29.4}$$

It should be noted that the increase in pressure is in proportion to the *absolute* temperature and not to the temperature as measured on the Fahrenheit scale.

Experiment shows that for all ordinary temperatures and pressures, *the pressure of a gas under constant volume varies directly as its absolute temperature*, provided the gas is not ncar the temperature at which it changes into a liquid.

In the foregoing discussion of the effects of heat upon gases no mention has been made of the weight of the gas, but the weight must be considered, because it exerts an influence upon the effects.

In the case of heating under constant pressure, the initial volume of the gas depends upon its weight. In the experiment of heating under constant pressure, mentioned above, the cylinder contained 2 cu. ft. of gas which weighed a certain amount. If the cylinder contained 4 cu. ft. of gas at the same temperature and pressure, or just twice as great a volume, the gas would have weighed twice as much as before and it would have required twice as much heat to raise its temperature the same amount.

In the case of heating under constant volume, the initial pressure of the gas in the cylinder depends upon the weight of the gas. If a certain weight of gas has a pressure 14.7 lb. per sq. in., the pressure of twice the weight would be 29.4, if the volume and temperature were the same as before. In this case, also, the amount of heat necessary to raise the temperature of the gas will depend upon its weight; twice the weight requiring twice as much heat to raise its temperature.

QUESTIONS

54. Explain the difference between pressure and vacuum, as these words are commonly used.

55. A certain water wheel in Arizona is supplied with water from a reservoir located 2100 ft. above the wheel. What is the pressure at the wheel?

56. The vacuum gage on a condenser reads 22 inches. What is the pressure in the condenser? (Assume atmospheric pressure to be 14.7 lb. per sq. in.)

57. What would be the pressure in the condenser mentioned in the preceding problem if the atmospheric pressure was 28.5 in. of mercury?

58. The pressure gage on a boiler reads 125 lb. per sq. in. The barometer reads 27.09 in. What is the absolute pressure of the steam in the boiler?

59. An aviator reads his barometer before starting and finds it stands at

28.65 in. While in his flight he reads the barometer and finds that it registers 24.53 in. How high above the surface of the earth is he?

60. The engineer of a power plant located 3960 ft. above sea level finds the vacuum gage on his condenser reads 22.48 in. The engineer of another power plant, located 2640 ft. above sea level, finds the vacuum gage on his condenser reads 25.67 in. Which of these two engineers is carrying the greater vacuum in his condenser?

61. An automobile tire containing 2093 cu. in. of air is pumped up to a pressure of 60 lb. per sq. in. when the temperature is 60° F. What will be the pressure in the tire on a day when the temperature is 96° F.?

62. Explain how a chimney can create a draft.

63. A warm air furnace has 8 warm air pipes leading from it, each 10 inches in diameter. Air enters the bottom of the furnace at a temperature of 0° F. and leaves the top of it at a temperature of 150° F. What should be the diameter of the pipe supplying cold air to the furnace in order that the velocity of the air in the cold air pipe may be the same as the velocity in the warm air pipes?

CHAPTER VII

LAWS OF GASES

53. Equation of Gases.—Since the volume of a gas varies in proportion to the absolute temperature, the pressure being constant, and since the pressure varies in proportion to the absolute temperature, the volume being constant, the two combined will also vary in proportion to the absolute temperature. The relation which exists between the pressure, volume, absolute temperature, and weight of a gas may be expressed by the following formula:

$$PV = WRT$$

In this equation

P = the absolute pressure of the gas in pounds per square foot (not pounds per square inch)
V = volume of the gas in cubic feet
W = weight of the gas in pounds
T = the absolute temperature of the gas
R = a constant, which depends upon the kind of gas

In the above formula, PV represents the amount of energy in the gas. Since the common unit for expressing energy is the foot-pound, P must be expressed in pounds per square foot, and V in cubic feet in order to make their product foot-pounds.

This is a very important equation in the study of gases, because it takes into account in one equation all of the things that may change, or are variable. The only variable quantities about a gas are the temperature, pressure, and volume, if we consider a constant weight of gas. The constant R is different for different gases, having the values shown in the following table:

VALUES OF R

Air	53.20
Carbon dioxide	35.11
Hydrogen	770.00
Nitrogen	55.20
Oxygen	48.20

If any four of the quantities in the above formula are known, the other one may be calculated, since the formula may be changed, as follows:

$$P=\frac{WRT}{V}$$

$$V=\frac{WRT}{P}$$

$$W=\frac{PV}{RT}$$

$$T=\frac{PV}{WR}$$

$$R=\frac{PV}{WT}$$

Examples:

1. A cylindrical tank 8 ft. in diameter and 20 ft. long contains air at a pressure of 60 lb. per sq. in. absolute and at a temperature of 90° F. What is the weight of the air in the tank?

Solution:

The volume of the air is

$$.7854\times 8^2\times 20=1005 \text{ cu. ft.}$$

The pressure of the gas is

$$60\times 144=8640 \text{ lb. per sq. ft.}$$

The absolute temperature is

$$90+460=550$$

The weight $W=\frac{PV}{RT}=\frac{8640\times 1005}{53.2\times 550}=297$ lb.

2. It is desired to store 80 pounds of air in a cylinder 3 feet in diameter and 8 feet long. What must be the gage pressure in the tank if the air is pumped in at a temperature of 120° F?

Solution:

Volume of the tank $=.7854\times 3^2\times 8=56.5$ cu. ft.
Absolute temperature of air $=120+460=580°$

$$P=\frac{WRT}{V}=\frac{50\times 53.2\times 580}{56.5}=27{,}300 \text{ lb. per sq. ft.}$$

$$=\frac{27{,}300}{144}=185.5 \text{ lb. per sq. in. absolute}$$

$$=185.5-14.7=170.8 \text{ lb. per sq. in. gage pressure}$$

It will be noted that, in the above equations, it is necessary

to know four of the five quantities which appear in the equation. That is, only those problems can be solved by means of this equation in which but one quantity is unknown, and in which but two quantities vary. Cases are sometimes met, in dealing with gases, in which two of the five quantities change. This is the case in measuring illumination gas when used in the gas calorimeter described in Chapter IV. In this case, the heating value of the gas should be expressed by B.T.U. per cu. ft. measured at atmospheric pressure (30 inches of mercury) and at a temperature of 60° F. When the volume of the gas is measured by a meter attached to the calorimeter, its pressure is usually more than 30 inches of mercury and its temperature may be more or less than 60° F. Hence, it is necessary to calculate the volume which the gas would occupy if its temperature was 60° F. and if it was under atmospheric pressure.

This kind of problem may be solved by using two equations and combining them. One of these equation would be:

$$P_1V_1=WRT_1$$

in which the letters have the same meaning as before, the subscript 1 being used to indicate the condition of the gas before the change. The other equations would be:

$$P_2V_2=WRT_2$$

the subscript 2 indicating another condition of the gas after the change. If the first equation be divided by the second, it will result in the equation

$$\frac{P_1V_1}{P_2V_2}=\frac{WRT_1}{WRT_2}$$

but, as W and R are the same in both cases, they may be omitted. The equation will then be

$$\frac{P_1V_1}{P_2V_2}=\frac{T_1}{T_2}$$

or

$$\frac{V_1}{V_2}=\frac{P_2}{P_1}\times\frac{T_1}{T_2}$$

The method of using this equation may be illustrated by the following example: A city gas company located near the natural gas fields pays 25 cents per 1000 cubic feet of gas under the

standard conditions of 14.7 lb. per sq. in. absolute pressure, and a temperature of 60° F. The gas is transmitted to it from the fields under a gage pressure of 300 lb. per sq. in. and the meter at the receiving end of the pipe line measures the high-pressure gas. On a certain day the meter shows that the city company used 20,000 cu. ft. of gas, measured at an average temperature of 90° F. How much does the city owe for this amount of gas?

The pressure of the gas as received is $P_2 = 300 + 14.7 = 314.7$ lb. per sq. in. absolute pressure. $P_1 = 14.7$ lb. per sq. in. absolute pressure. The temperature as received is $T_2 = 90 + 460 = 550°$ absolute and the standard temperature $T_1 = 60 + 460 = 520°$ absolute. The volume received is V_2, 20,000 cu. ft.

$$\frac{V_1}{V_2} = \frac{P_2}{P_1} \times \frac{T_1}{T_2}$$

$$\frac{V_1}{20{,}000} = \frac{314.7}{14.7} \times \frac{520}{550}$$

$$V_1 = \frac{20{,}000 \times 16{,}364.4}{808.5} = 404{,}809 \text{ cu. ft.}$$

or

$$\frac{404{,}809}{1{,}000} = 404.809 \text{ thousands of cu. ft.}$$

The city company therefore owes for this amount of gas

$$\$.25 \times 404.809 = \$101.20$$

54. Specific Heat of Gases.—As with solids and liquids, a certain amount of heat is absorbed in raising the temperature of a gas and, in cooling, a gas gives out a certain amount of heat. The amount of heat absorbed or given out by one pound of a gas when its temperature changes one degree is called its specific heat. However, a gas differs from a solid or a liquid in that its volume may be held constant while its temperature is being changed. In this case its pressure changes. Or, the pressure of a gas may be held constant while its temperature is being changed. In this case its volume changes. It thus happens that any gas has two specific heats, a specific heat at constant volume and a specific heat at constant pressure.

When a gas is heated while it is under a constant pressure two effects will be observed; first, an increase in temperature; and second, an increase in volume. Both of these effects are produced by the heat supplied to the gas and each of them requires a certain amount of heat. That part of the heat which increases

the temperature is utilized in causing the molecules of the gas to vibrate faster and that part which causes an increase in volume is utilized in doing external work. This external work consists in changing the volume of the gas against the pressure upon it and, since it is work, heat energy is required.

The total number of heat units required to change the temperature of a gas under constant pressure may be calculated by the formula

$$H = C_p(t_1 - t)W$$

in which C_p = specific heat of the gas at constant pressure
t_1 = higher temperature
t = lower temperature
W = the weight of the gas in pounds

This amount of heat includes both that required to change the temperature and that required to change the volume.

When the temperature of a gas is increased, heat is absorbed by the gas, and when its temperature is lowered, the gas gives out heat, but the number of heat units transferred will be the same in either case, provided the range in temperature is the same. Therefore, the above formula may be used to calculate either the amount of heat absorbed by a gas in raising its temperature or the amount given up by a gas in lowering its temperature when the pressure remains constant.

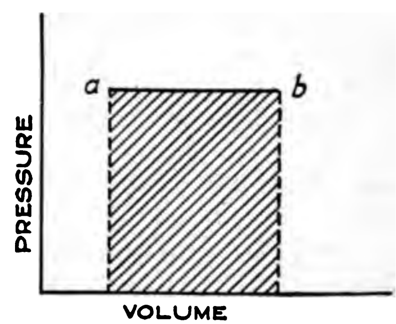

Fig. 53.

The change of volume of a gas heated at constant pressure is shown in Fig. 53. The original volume of the gas is indicated by the point a, while the point b indicates its volume after being heated. Expansion occurs with a constant pressure from a to b, and the work performed during the expansion is shown by the shaded area. The work in foot pounds performed by the gas is equal to the change in volume, expressed in cubic feet, multiplied by the constant pressure, expressed in pounds per square foot, or

$$\text{Work} = P(V_2 - V_1)$$

in which V_2 = larger volume of gas in cubic feet
V_1 = smaller volume of gas in cubic feet
P = the constant pressure of the gas in lb. per sq. ft.

If it is desired to express the work performed in terms of heat units it may be done by dividing by the mechanical equivalent of a heat unit, 778, thus:

$$\text{Work (in B.T.U.)} = \frac{P\,(V_2 - V_1)}{778}$$

It should be noted that the area under the expansion curve, in Fig. 53, shows only the external work performed by the gas in changing its volume from a to b, and it does not show the amount of heat used in changing the temperature of the gas.

When the temperature of a gas is changed while its volume remains constant no external work is performed and all of the heat supplied to the gas is used in changing its temperature. This amount of heat may be calculated by the formula

$$H = C_v(t_1 - t)W$$

in which C_v is the specific heat of the gas under constant volume, and the other letters have the same meaning as before. In heating under constant volume, the heat is used for no other purpose than to change the temperature, hence this formula may be used for calculating the amount of heat used in changing the temperature alone of a gas under any conditions.

In heating a gas under constant pressure it has been shown that the total amount of heat absorbed is

$$C_p(t_1 - t)W$$

and also that the amount of heat used in performing external work is

$$\frac{P(V_2 - V_1)}{778}$$

The remainder of the heat is used in changing the temperature of the gas, and this amount of heat is

$$C_v(t_1 - t)\ W$$

Therefore the sum of the heat used in performing external work,

$$\frac{P(V_2 - V_1)}{778}$$

and the heat used in changing the temperature of the gas,

$$C_v(t_1-t)W,$$

is equal to the total amount of heat absorbed by the gas when it is heated at constant pressure, or

$$C_p(t_1-t)W=\frac{P(V_2-V_1)}{778}+C_v(t_1-t)W$$

In changing the temperature of a gas under constant pressure, enough heat must be transferred to change not only the temperature but also the volume of the gas, while in changing the temperature under constant volume, only enough heat is transferred to change the temperature alone. Hence, it follows that the specific heat of a gas under constant pressure, C_p, will always be larger than its specific heat under constant volume C_v. The following table, which gives the specific heats of a few of the gases, shows this to be true.

SPECIFIC HEATS OF GASES

Gas	Specific heat at constant volume C_v	Specific heat at constant pressure C_p
Air	.1691	.2375
Carbon dioxide	.1434	.1886
Hydrogen	2.415	3.406
Nitrogen	.173	.244
Oxygen	.1550	.217

In this table it will be noted that in every case the specific heat under constant pressure is larger than that under constant volume. The difference is the amount of heat transferred in changing the volume alone of the gas; that is, the external work which the gas does in changing its volume under constant pressure.

Examples:

1. A closed air tank contains 50 pounds of air at a temperature of 40° F. How many heat units will be required to raise its temperature to 120° F.?

Solution:

The number of heat units required to raise the temperature of one pound of the air is

$$H=C_v(t_1-t)=.1691\ (120-40)$$
$$=.1691\times 80=13.528\text{ B.T.U.}$$

Therefore the number of heat units required to raise the temperature of 50 pounds will be

$$50\times 13.53=676.5\text{ B.T.U.}$$

2. How many heat units are required to change the temperature of the air in the previous example if the air is under constant pressure instead of under constant volume?

Solution:

For one pound of air

$$H = C_p(t_1 - t) = .2375\ (120-40)$$
$$= .2375 \times 80 = 19 \text{ B.T.U.}$$

For 50 pounds the heat required is

$$50 \times 19 = 950 \text{ B.T.U.}$$

With the data given in these examples, the amount of heat used in changing the volume of the air (the external work) may also be calculated. The amount of heat absorbed in changing the temperature of the air under constant volume is 950 B.T.U. which includes both the heat used in changing temperature and in performing external work. Since the amount of heat used in changing temperature is 676.4 B.T.U., the amount used in performing external work is

$$950 - 676.4 = 273.6 \text{ B.T.U.}$$

and the number of foot-pounds of external work performed is

$$273.6 \times 778 = 212{,}861 \text{ ft.-lb.}$$

It is to be observed that the specific heats given in the table above are expressed in heat units. They may also be expressed in foot-pounds by multiplying them by 778, the number of foot-pounds in one heat unit. The value of the constant R in the equation

$$PV = WRT$$

is equal to the difference between the specific heats at constant pressure and constant volume expressed in foot-pounds, or

$$R = (C_p - C_v)778$$

For example, R for air is equal to

$$R = (C_p - C_v)778 = (.2375 - .1691)778$$
$$= .0684 \times 778 = 53.21$$

QUESTIONS

64. Why is the specific heat of a gas at constant pressure greater than its specific heat at constant volume?

65. What does the difference between the specific heats of a gas at constant pressure and at constant volume represent?

66. A balloon at sea level contains 1000 cu. ft. of hydrogen at a temperature of 60° F., what is the weight of the hydrogen in the balloon?

67. What is the weight of air displaced by the balloon mentioned in Question 66? How many pounds could this balloon lift?

68. A four cycle gas engine has a cylinder 12 in. in diameter, a stroke of 15 in., and a clearance of 25 per cent. What weight of gas (mixture of gas and air) is taken into the cylinder during the suction stroke, the temperature of the mixture being 100° F.? (Assume R for the mixture to be the same as for air.)

69. If the pressure in the above engine is 180 lb. per sq. in. at the end of compression what is the resulting temperature?

70. What will be the pressure of the gas after explosion if the mixture has a heating value of 60 B.T.U. per cu. ft.? (Assume specific heat to be same as for air.)

71. In pumping water with an ordinary hand pump why is more force required at each stroke until water begins to flow?

72. A diver descends 120 ft. below the surface of the water. What is the pressure to which he is subjected?

73. A cubic foot of air escaping from the suit of the diver mentioned above has a temperature of 40° F. What will be its volume when it reaches the surface of the water?

74. An automobile tire is pumped up to a pressure of 70 lb. per sq. in. at 90° F. If it will burst at a pressure of 120 lb. per sq. in. to what temperature must it be heated before it will burst?

75. The chimney on a power house is 100 ft. high and 6 ft. diameter inside. The average temperature of the gases inside is 350° F. What is the weight of the gases inside the chimney? (Use same value of R as for air.)

76. What is the weight of a volume of air outside the chimney equal to that of the volume of gases in the above chimney, the air having a temperature of 90° F.?

77. What is the draft of the above chimney in ounces per sq. in., the draft being caused by the difference in weight at the bottom of the chimney of the air and hot gases?

CHAPTER VIII

COMPRESSION AND EXPANSION OF GASES

55. Effects of Compression and Expansion upon Temperature. —When a gas is compressed there is always a tendency for its temperature to increase. The fact that a bicycle pump becomes hot while pumping air into a tire is a familiar example of this. On the other hand, there is a tendency for the temperature of a gas to decrease when it is expanded. In the case of the bicycle pump mentioned above it will be observed that the faster the pump is operated the hotter it will become, which shows that the *time* taken to compress a pump full of air exerts some influence upon the temperature of the compressed air. If it were desired to prevent any increase in temperature during compression, this result could be secured by operating the pump very slowly. In this case, any heat developed in the air during compression would have sufficient time to reach the walls of the pump and be given off to the atmosphere by radiation and conduction, and, since it is taken out of the compressed air, there would be no increase in temperature. If, on the other hand, the pump were made of a perfectly non-conducting substance so that none of the heat developed in the air during compression could leave it, all of it would remain in the air and produce the greatest increase in temperature which this amount of compression is capable of producing. The maximum increase in temperature would also be obtained by performing the compression so quickly that none of the heat developed would have time to leave the air.

It is thus seen that the increase in temperature produced by compressing air may vary from nothing to a maximum depending upon the conditions under which the compression is performed. If, by any means, the heat developed in the air during compression is removed as fast as it is developed there will be no increase in temperature, but if, on the other hand, no heat is removed during compression, all of it will remain in the air and produce the maximum increase in temperature. Between these two extremes, the temperature of the air will increase any amount

during compression depending upon the amount of heat removed from the air during compression. The above statements have referred only to air, but the same effects will be produced in any other gas. The same amount of compression under the same conditions may, however, produce in different gases a different increase in temperature, depending upon the nature of the gas.

Since expansion is the reverse of compression the effects of expansion are opposite to those of compression. Compression increases the pressure and decreases the volume, while expansion reduces the pressure and increases the volume. The temperature of a gas tends to increase during compression and to decrease during expansion. Moreover, if compression and expansion occur under the same conditions the decrease in temperature during expansion will be the same as the increase during compression. Therefore, in discussing the effects of compression and expansion upon gases, it is necessary to mention the effects of only one of these operations.

It has been shown above that the conditions under which a gas is compressed or expanded determine its increase or decrease of temperature. For the same amount of compression, that is, for the same decrease in volume, the increase of temperature is controlled by the amount of heat which escapes or is removed from the gas during compression. If all of the heat escapes as fast as it is developed there will be no increase of temperature, and if only a part of the heat developed escapes there will be some increase in temperature, but not as much increase as if no heat escaped. In all cases the increase in temperature will depend upon the decrease in the amount of heat in the gas.

For the same decrease in volume during compression, the increase of pressure of the gas will depend upon the increase in temperature. If the conditions under which the gas is compressed are such as to produce a large increase in temperature, the increase in pressure will also be large; but if the conditions of compression are such as to produce a small increase in temperature, the increase in pressure will be less. This is illustrated by Fig. 54 which shows the increase in pressure when 8 cubic feet of air is compressed until its volume is 2 cubic feet. This figure shows four separate compression lines and also shows the increase in pressure when air is compressed under different conditions so as to produce different increases of temperature. In each case the pressure and temperature at the beginning of compression

is the same, but the temperature and therefore the pressure at the end of compression is different for the different curves.

The compression line OA shows the increase in pressure when the air is compressed in such manner that there will be no increase of temperature, the temperature at the beginning and end of compression being 60° F. The second curve, OB, shows the increase in pressure when the air is compressed in such manner that its temperature at the end of compression will be 100° F., an increase of 40° during compression. The third compression

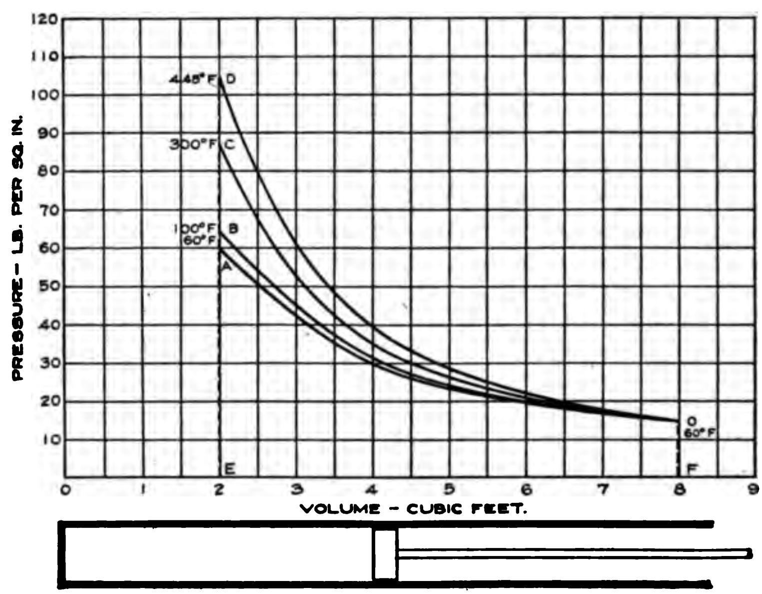

FIG. 54.

line, OC, is for conditions under which the final temperature of the air is 300° F., an increase of 240° during compression. The fourth compression line, OD, is for the condition in which no heat escapes from the air during compression, which causes the maximum increase in temperature for this amount of compression. In this case the final temperature of the air is 445° F., an increase of 385°.

56. Isothermal Compression and Expansion.—It has been shown in Chapter VII that a gas may change as to pressure,

volume, and temperature, but that these always vary in such a way that, for one pound of gas,

$$PV = RT$$

This formula may be rearranged into

$$\frac{PV}{T} = R$$

which shows that, since R is a constant quantity depending only upon the kind of gas, the pressure and volume multiplied together and divided by the absolute temperature is always a constant quantity, regardless of the way in which the pressure, volume, and temperature change with respect to each other. Therefore, when the compression is such as to maintain a constant temperature, as illustrated by the line OA in Fig. 54, the relation between pressure and volume at the beginning and end of compression will be such that

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_1}$$

in which P_1, V_1, and T_1 represent the pressure, volume, and temperature of the gas at the beginning of compression and P_2 and V_2 represent the pressure and volume of the gas at the end of compression. Referring to the compression line OA, Fig. 54, it will be noted that the absolute temperature of the gas, both at the beginning and end of compression, is 520° (60° F.); therefore the formula representing the change of pressure and volume during compression is

$$\frac{P_1V_1}{520} = \frac{P_2V_2}{520}$$

or, more simply,

$$P_1V_1 = P_2V_2$$

In this case the pressure and volume at the beginning of compression are $P_1 = 15$ lb. per sq. in. and $V_1 = 8$ cu. ft. The volume at the end of compression is $V_2 = 2$ cu. ft.
Therefore the formula

$$P_1V_1 = P_2V_2$$

becomes

$$15 \times 8 = P_2 \times 2$$

or the pressure at the end of compression is

$$P_2 = \frac{15 \times 8}{2} = 60 \text{ lb. per sq. in.}$$

When a gas is compressed or expanded in such manner that the temperature remains constant, the pressure and volume will vary so that the product obtained by multiplying them together will be a constant quantity for any point in the compression or expansion, that is,

$$PV=C$$

in which C is a constant quantity. In the case of the compression line OA, Fig. 54, the product obtained by multiplying together the pressure and volume at the beginning of compression is

$$PV=C$$
$$15\times 8=120$$

and the product of pressure and volume at any other point on the curve is the same. Thus, when the volume has reached 4 cu. ft. the pressure will be 30 lb. per sq. in., because

$$4\times 30=120$$

and when the volume has reached 2 cu. ft. the pressure will be 60 lb. per sq. in., because

$$2\times 60=120$$

Example:

In the above case, what will be the pressure of the air when the volume is 6 cu. ft.?

Solution:

$$PV=C=120$$

$$P=\frac{C}{V}=\frac{120}{6}=20 \text{ lb. per sq. in.}$$

The kind of compression or expansion in which the temperature of the gas remains constant is called *isothermal* (meaning constant temperature) compression or expansion. The compression line OA, Fig. 54, is for isothermal compression, since the temperature of the gas remains constant at 60° F. while it is being compressed from the point O to the point A.

The work performed during an isothermal compression or expansion is equal to the area under the compression or expansion line, as the area $OAEF$, Fig. 54. This work may be calculated by the formula

$$W=331.6\ P_1V_1 \log \frac{V_2}{V_1}$$

in which W = work of compression or expansion, in foot-pounds
P_1 = absolute pressure at end of compression or beginning of expansion, in lb. per sq. in.
V_1 = volume at end of compression or beginning of expansion in cu. ft.
V_2 = volume at beginning of compression or end of expansion in cu. ft.

$$\log \frac{V_2}{V_1} = \text{logarithm of } (V_2 \div V_1)$$

Example:

How much work is required to compress the air for which OA in Fig. 54 is the compression line?

Solution:

P_2 = pressure at beginning of compression = 15 lb. per sq. in.
V_2 = 8 cu. ft.
V_1 = 2 cu. ft.

$$P_1 = \frac{P_2V_2}{V_1} = \frac{15\times 8}{2} = 60 \text{ lb. per sq. in.}$$

$$\frac{V_2}{V_1} = \frac{8}{2} = 4$$

$$W = 331.6\,P_1V_1 \log 4$$
$$= 331.6\times 60\times 2\times .60206$$
$$= 23{,}957 \text{ ft.-lb.}$$

It will be observed from Fig. 54 that in the isothermal compression of a gas the pressure and volume vary inversely with each other, *i.e.*, the pressure increases in the same proportion that the volume decreases. When the pressure has doubled (30 lb. per sq. in.) the volume has become one-half (4 cu. ft.) and when the pressure has reached four times its original value (60 lb. per sq. in.) the volume has become one-fourth its original value (2 cu. ft.). It will be observed also that when the temperature of the gas increases during compression, the pressure increases faster than the volume decreases. For example, the compression line OD, Fig. 54, shows that when the volume becomes one-half (4 cu. ft.) the pressure has increased to 39.6 lb. per sq. in., which is more than twice the original pressure (15 lb. per sq. in.). The reason for this is that, when the temperature increases during compression, part of the heat developed during compression remains in the gas and serves to increase its pressure; hence, the greater the increase in temperature during compression the greater the increase in pressure for a given volume will be. The greater increase in pressure when there is an increase in temperature

during compression requires that more work be performed in compressing a gas through a given range of volume than if there were no increase in temperature. This is plainly shown by Fig. 54. In each case of compression shown, the work performed in compressing the gas is indicated by the area under the compression line, and this area becomes larger with an increase in the final temperature of the gas. It will be further observed from Fig. 54 that an isothermal compression requires the least amount of work to compress through a given range of volume, hence this is the most ecónomical kind of compression. This fact is of particular importance in the compression of air; and air compressors are designed to keep the air as cool as possible during compression. The most common means employed to secure this result is to surround the air compressing cylinder with a jacket through which cold water is circulated.

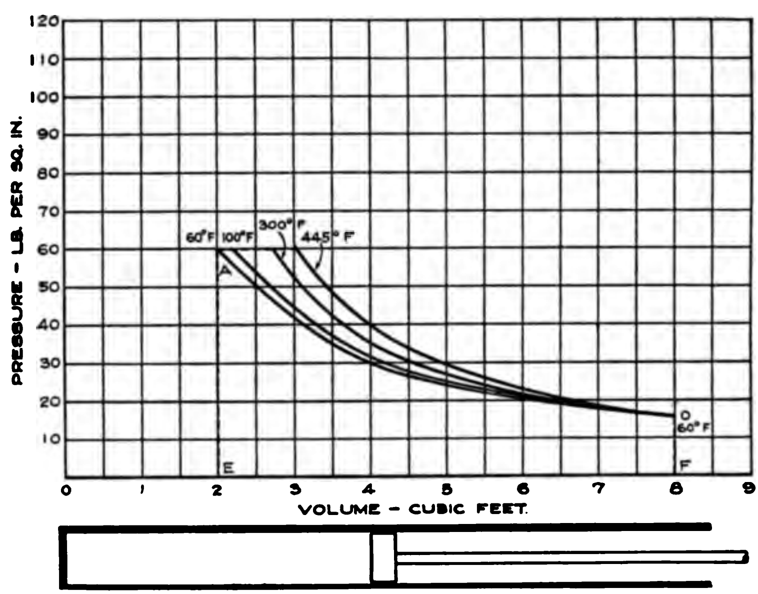

FIG. 55.

57. Compressing with Increase of Temperature.—While a water jacket surrounding a compressing cylinder serves to lower the final temperature of the air or other gas that is being compressed, it is impossible to prevent some increase in temperature, hence the study of compressions and expansions in which there is a change of temperature is important.

In Fig. 54 the compression lines OA, OB, OC, and OD show the relation between pressure and volume when air is compressed under various conditions but through the same range of volume, namely, from 8 cu. ft. to 2 cu. ft. In Fig. 55 the same lines are shown for the same conditions except that in each case the air is compressed through the same range of *pressure.* The line OA is for no increase in temperature and OD for the maximum increase in temperature.

It will be observed from Fig. 55 that the greater the increase in temperature during compression the steeper the compression line will be; that is, the greater the increase in temperature the less the volume will change for a given change in pressure. When there is a change of temperature during compression or expansion, the relation between the pressure and the volume at any point is shown by the following formula:

$$PV^n = C$$

in which P = pressure of the gas, in lbs. per sq. in.
V = corresponding volume, in cu. ft.
C = a constant quantity
n = a number varying with the kind of gas and the nature of the compression; that is, the extent to which heat is removed during compression

The relations between pressure and volume, between pressure and temperature, and between volume and temperature for any two points on the compression or expansion line, when there is a change in temperature, is shown by the following ratios:

$$P : P_1 :: V_1^n : V^n$$

$$V_1 : V :: P^{\frac{1}{n}} : P_1^{\frac{1}{n}}$$

$$T : T_1 :: P^{\frac{n-1}{n}} : P_1^{\frac{n-1}{n}}$$

$$T : T_1 :: V_1^{n-1} : V^{n-1}$$

In all of the above ratios the quantities P, V, and T refer to any single point on the compression or expansion line, and the quantities P_1, V_1, and T_1 refer to any other single point. The temperatures T and T_1 are the absolute temperatures and not the temperature as read on the Fahrenheit scale. The quantity n, as before, depends upon the kind of gas and the nature of

the compression or expansion, and it is the same quantity that appears in the formula

$$PV^n = C$$

The smallest value of n is 1, in which case the compression or expansion is isothermal. The value of n becomes larger when a smaller amount of heat is removed from the gas during compression, or when a smaller amount of heat is absorbed by a gas during expansion. Its greatest value is equal to the ratio of the specific heat of the gas at constant pressure to its specific heat at constant volume, or

$$\text{greatest value of } n = \frac{C_p}{C_v}$$

The use of the ratios given above may be illustrated by the following example:

Example:

8 cu. ft. of air at 15 lb. per sq. in. pressure are compressed until the pressure is 60 lb. per sq. in. in such manner that $n = 1.4$. What will be the volume of the air after compression?

Solution:

In this case the ratio

$$V_1 : V :: P^{\frac{1}{n}} : P_1^{\frac{1}{n}}$$

may be used. This ratio may be changed to read

$$\frac{V_1}{V} = \left(\frac{P}{P_1}\right)^{\frac{1}{n}}$$

or

$$V_1 = V\left(\frac{P}{P_1}\right)^{\frac{1}{n}}$$

$V = 8$ cu. ft.
$P = 15$ lb. per sq. in.
$P_1 = 60$ lb. per sq. in.
$n = 1.4$

Therefore

$$V_1 = 8\left(\frac{15}{60}\right)^{\frac{1}{1.4}} = 8\left(\frac{1}{4}\right)^{.7143} = 2.9 \text{ cu. ft.}$$

It is necessary to use logarithms in making this calculation, the operation being as follows:

$$\text{Log. } 8 + .7143 \text{ Log. } \tfrac{1}{4} = \text{Log. } V_1$$
$$.9031 + (.7143 \times 9.3974 - 10) =$$
$$.9031 + (9.5696 - 10) = .4729$$
$$\text{Log. } V_1 = .4729$$
$$V_1 = 2.9$$

58. Adiabatic Compression and Expansion.—When a gas is compressed or expanded in such manner that no heat can enter or leave it the compression or expansion is said to be *adiabatic.* In adiabatic compression, since no heat leaves the gas, all of the heat developed during compression remains in the gas and increases its temperature. The increase in temperature under this condition will be the greatest possible without the use of external heat. In adiabatic expansion, since no heat enters the gas, the work of expansion is performed by the heat stored in the gas and when this heat is turned into work the temperature of the gas decreases. Under this condition the decrease in temperature is the greatest possible.

With adiabatic compression or expansion the pressure and volume vary in such manner that

$$PV^n = C$$

in which n has a value equal to the specific heat of the gas at constant pressure divided by its specific heat at constant volume, or

$$n = \frac{C_p}{C_v}$$

For air the value of n is

$$n = \frac{C_p}{C_v} = \frac{.2375}{.1691} = 1.405$$

For most practical problems relating to air a value of $n = 1.4$ may be used. Using this value of n, the above formula showing the relation between pressure and volume during an adiabatic compression or expansion of air becomes

$$PV^{1.4} = C$$

59. Work Performed.—In any case of compression or expansion the work performed is represented by the area under the compression or expansion line. When there is a change of temperature during compression or expansion the work performed may be calculated by the formula

$$W = 144\ \frac{P_1V_1 - P_2V_2}{n-1}$$

in which W = Work of compression or expansion, in foot-pounds

P_1 = Pressure at end of compression or beginning of expansion, lb. per sq. in.

V_1 = Volume at end of compression or beginning of expansion, cu. ft.

P_2 = Pressure at beginning of compression or end of expansion, lb. per sq. in.

V_2 = Volume at beginning of compression or end of expansion, cu. ft.

n = Number depending upon kind of gas and character of the compression or expansion.

In the above formula it will be noted that P_1 and P_2 are expressed in lb. per sq. in. Because of this it is necessary to use the factor 144 in order that W may be expressed in foot-pounds.

Example:

How much work must be performed upon 8 cu. ft. of air at 15 lb. per sq. in. pressure in order to compress it adiabatically until its volume is 2 cu. ft. ($n = 1.4$)?

Solution:

$P = 15$
$V = 8$
$V_1 = 2$

In order to find the value of P_1 use the ratio, given above,

$$P : P_1 : : V_1^n : V^n$$

or

$$P_1 = P\left(\frac{V}{V_1}\right)^n = 15\left(\frac{8}{2}\right)^{1.4} = 15 \times 4^{1.4} = 104.5 \text{ lb. per. sq. in.}$$

(Note: $4^{1.4}$ is the same as $4^{\frac{7}{5}}$ or $\sqrt[5]{4^7}$).

$$W = 144\frac{P_1V_1 - P_2V_2}{n-1}$$

$$= 144\,\frac{104.5\times 2 - 15\times 8}{1.4-1} = 144\frac{209-120}{.4}$$

$$= 144\frac{88}{.4} = 144\times 222.5 = 31{,}040 \text{ ft. lb.}$$

An adiabatic compression gives the greatest increase in temperature and an isothermal compression gives the least increase. Between these two extremes the compression may be performed in such manner as to produce any increase in temperature. The greater the increase in temperature, the faster the pressure increases in proportion to the decrease in volume, and the greater the value of the exponent n will be.

In the compression of air it is desirable to prevent, as much as possible, an increase in temperature, and the compressing

cylinder is supplied with a water jacket for this purpose. This, however, produces but little cooling effect. The increase in temperature will vary somewhat with the kind of compressing cylinder and the speed of compression, varying in such way that the relation between pressure and volume will be from

$$PV^{1.25}=C$$

to

$$PV^{1.35}=C$$

This shows that the compression is beween isothermal and adiabatic, usually being nearer an adiabatic and producing considerable increase in temperature. After being compressed and discharged from the cylinder the temperature of the air decreases until it is the same as that of surrounding objects. This is particularly true when the compressed air is stored for any length of time or is transmitted through pipes for some distance.

Compressed air is sometimes used to run engines or other machines in which the air is expanded. The expansion in these cases is such that the relation between pressure and volume is from

$$PV^{1.3}=C$$

to

$$PV^{1.35}=C$$

This gives an expansion line which is quite close to an adiabatic and results in a considerable decrease in temperature during expansion. One of the principal objections to the expansive use of compressed air is that the low temperatures produced by expansion cause moisture in the air to freeze and stop the exhaust ports and passages with frost. The temperature of the compressed air at the beginning of expansion will be but little above that of surrounding objects, perhaps not more than 100° F. If the expansion occurs through a considerable range of pressure, the decrease in temperature will be large and frost will be formed. One method of preventing the formation of frost is to pre-heat the air, that is, to pass it through a heater just before it enters the cylinder. By raising its temperature to about 300° or 350° F., which will be the temperature at the beginning of expansion, the temperature at the end of expansion will not fall below the freezing point.

In a gas engine the cylinder is filled with a mixture of gas and air, called the charge, which is compressed as shown by the

compression line AB in Fig. 56. In this case an adiabatic compression would be desirable because this gives a high temperature of the charge at the end of compression, when the explosion or burning of the fuel occurs. The burning of the fuel occurs just at the end of the compression stroke and liberates a quantity of heat which increases the temperature of the gases in the cylinder. The heating at constant volume which occurs at this point is shown by the line BC in Fig. 56. The liberation of heat by the fuel produces a definite increase in temperature, hence if the temperature at the end of compression is high, the temperature of the gases at the beginning of expansion will also be high. This gives a high pressure at the beginning of the

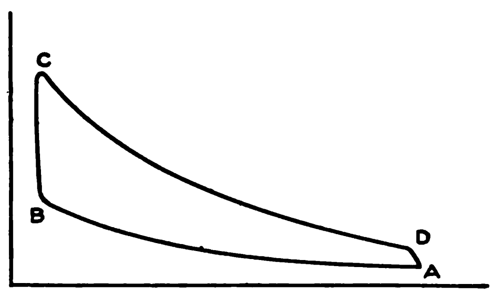

Fig. 56. Gas engine indicator diagram.

expansion stroke and the gases are therefore capable of performing more work than if the compression pressure was lower. The expansion in a gas engine as shown by the line CD is usually very close to an adiabatic, as well as the compression line AB.

Cylinders of gas engines are cooled by water jackets or other means, but, as with air compressor cylinders, the cooling has but little effect upon the gases in the cylinder, as the speed is high and the transmission of heat from gas to metal is slow. Since the temperatures developed in a gas engine are very high, cylinder cooling has the good effect, however, of preventing the cylinder from becoming too hot.

QUESTIONS

78. Explain the difference between isothermal and adiabatic expansion or compression of a gas.

79. Why is there always a tendency for the temperature of a gas to rise during compression and to fall during expansion?

80. In compressing air, which requires more power; to compress it at constant temperature, or to allow the temperature to rise? Give the reasons for your answer.

81. Why does the pressure rise faster for a given decrease of volume during adiabatic compression than during isothermal compression?

82. An air compressor having a cylinder 24 in. in diameter, a stroke of 30 in., and with 8 per cent. clearance compresses air to a gage pressure of 70 lb. per sq. in. from atmospheric pressure (14.7 lb. per sq. in.). What is the volume of compressed air at 70 lbs. gage discharged at each stroke? (Assume value of $n = 1.35$.)

83. If the air is taken into the cylinder of the above compressor at a temperature of 90° F., what will be its temperature at the end of compression?

84. How many foot-pounds of work are required to compress the air during a single stroke of the compressor mentioned in Question 82?

85. The compressor mentioned in Question 82 is double acting and makes 80 R.P.M. How many horse-power are required to compress and discharge the air at the discharge pressure?

86. If the compressor mentioned in Question 82 had compressed the air isothermally, what volume of compressed air would it have discharged at each stroke?

87. Compressed air at a pressure of 75 lb. per sq. in. gage and a temperature of 100° F. is expanded adiabatically until its pressure is 5 lb. per sq. in. gage. What will be its temperature at the end of expansion?

CHAPTER IX

PROPERTIES OF STEAM AND OTHER VAPORS

60. Steam.—Any of the gases which have been mentioned in preceding chapters may be changed into liquids if their temperatures are reduced low enough and they are placed under the proper pressure. Thus, at atmospheric pressure, air changes into a liquid at $-313°$ F., and hydrogen at $-423°$ F. At ordinary temperatures these substances are very far removed from the point at which they liquefy. For this reason and because it is difficult to change them into liquids they are called permanent gases. Permanent gases follow the rules regarding pressure, volume, and temperature which have been considered in previous chapters, but if these gases were near the temperature at which they change into liquids, they would not follow these rules. When a substance in a gaseous condition is at or near the temperature at which it changes into a liquid it is called a vapor, and when it is far removed from this temperature it is called a gas.

Steam is water vapor which has a temperature at or near that at which it changes into a liquid and for this reason the rules and formulas applying to gases do not apply to it. Steam has its own characteristics, or properties, and its own rules relating to pressure, volume, temperature, etc.

61. Evaporation.—Steam is formed by applying heat to water and evaporating it. If we take an ordinary tea-kettle or pan containing water, and place it over a fire the temperature of the water will increase until it is somewhere near 212° F., when it will begin to boil and give off steam. After the water begins to boil, its temperature remains constant. If heat is applied faster to the water, it boils more violently and if heat is applied slower the water boils slower, but in either case its temperature does not change. If one thermometer is placed in the boiling water and another is placed in the steam above the water both will be found to register the same, showing that the steam and the water have the same temperature.

In the case mentioned above, where the water is heated in a tea-kettle, the boiling water is under only atmospheric pressure, 14.7 lb. per sq. in. absolute. If the water is boiled in a closed vessel under a pressure greater than that of the atmosphere, the water must be heated to a higher temperature than 212° F. before it will boil. On the other hand, if a pressure less than that of the atmosphere is maintained in the vessel by means of a vacuum pump, or otherwise, the water will boil at a lower temperature than 212° F. Experiment shows that for each pressure at which steam is formed there is a definite corresponding boiling temperature, and that the temperature of the steam is always the same as that of the boiling water. If the pressure is great the corresponding boiling temperature is high and if the pressure is low the corresponding boiling temperature is low. That is, for each different pressure under which steam is formed there will be a definite boiling temperature.

The temperature of steam formed at any pressure cannot be increased as long as the steam is in contact with water. Any attempt to increase the temperature of the steam by applying more heat will only result in evaporating more water. The temperature of steam may, however, be increased if it is removed from the presence of water and heat applied to it. The temperature of steam may also be changed if it is removed from the presence of water and its pressure changed. The temperature of the steam will then be the same as the boiling point corresponding to its new pressure. Thus, when steam is admitted to the cylinder of a steam engine it has a high pressure and a high temperature. When the steam is exhausted its pressure has been reduced by expansion and it will have a correspondingly low temperature.

62. Heat of the Liquid.—Any substance which has a temperature above absolute zero contains some heat, hence before the water is heated in the tea-kettle it already contains some heat and the process of changing it into steam is a process of adding more heat to that already in the water. In order to have a definite point from which to calculate the amount of heat added to the water in forming steam, the freezing temperature of water, 32° F., is chosen, and all quantities of heat added are calculated from this temperature. The amount of heat added to water, above 32° F. to form steam, is often called the heat contained in the steam or the total heat of the steam. It should be re-

membered, however, that this quantity is not all of the heat which the steam contains but is only the amount that has been added above the starting point, 32° F.

In the case of heating water in a tea-kettle, as mentioned above, it will be observed that the formation of steam consists of two distinct parts: first, heating the water to the boiling point; and second, after the water has reached the boiling point, supplying more heat to change it into steam.

The quantity of heat that must be added to water to raise its temperature from 32° F. to the boiling point is called the *heat of the liquid.* Since the boiling temperature depends upon the pressure acting upon the water, the water having a different boiling temperature for each different pressure, there will also be a different heat of the liquid for each different pressure. Since one B.T.U. will raise the temperature of one pound of water one degree, the heat of the liquid will be equal, approximately, to the boiling temperature minus 32°. Thus, at atmospheric pressure (14.7 lb. per sq. in.) the boiling temperature is 212° F.; hence the heat of the liquid is

$$212-32=180 \text{ B.T.U. per pound of water.}$$

This method of calculating the heat of the liquid gives only approximately correct results, because at some temperatures one B.T.U. will raise one pound of water more than one degree, and at other temperatures less than one degree.

63. Latent Heat of Steam.—The heat that must be added to water after it has reached the boiling point, in order to turn it into steam, is called the *latent heat.* This part of the heat is called "latent" because it does not affect a thermometer, or change the temperature. Heat which affects a thermometer, or is sensible to the touch, is sometimes called "sensible" heat to distinguish it from "latent" heat which cannot be felt. In this sense, the heat of the liquid is sensible heat.

Although the temperature of boiling water does not change, large quantities of heat must be added to change it into steam. The heat added at this time, called the latent heat, is several times as large as the heat of the liquid. Thus, at atmospheric pressure (14.7 lb. per sq. in.) the heat of the liquid is only 180 B.T.U. per pound of water. The latent heat is 970.4 B.T.U. per pound of steam. The heat of the liquid is utilized in increasing the temperature of the water while the latent heat is utilized in

breaking down the attraction of the molecules of water for each other, thus changing it from water into steam, and also in expanding the water into steam against the pressure existing on the surface of the water. Since the amount of heat required to do each of these things is large, the latent heat is much larger than the heat of the liquid.

64. Total Heat of Steam.—The total heat of steam is all of the heat required to heat water from 32° F. to the boiling point and then to change it into steam. It is therefore the sum of the heat of the liquid and the latent heat. If we denote the heat of the liquid of one pound of steam by h and the latent heat of one pound by L, then the total heat H, of one pound of steam, will be

$$H=h+L$$

It should be noted that the total heat of steam is measured above 32° F., for the same reason that the heat of the liquid is measured above this temperature.

65. Steam Tables.—A great many problems relating to the use of steam make it necessary to know the exact amount of heat used in generating each pound of steam, and, in some cases, also the volume of the steam. All such quantities as these, including the temperature, heat of the liquid, latent heat, total heat, volume, and density, are called the "properties of steam." These quantities have been observed and recorded for our use by various scientists, and the results of their observations have been arranged in tables which we call, for short, *Steam Tables*. The quantities given in the steam tables are for one pound weight of water or steam; hence, in order to find the heat of the liquid, latent heat, total heat, or volume of *any* weight of steam it is necessary to multiply the quantity given in the steam table by the weight of water or steam. A steam table for the use of students in this course will be found at the end of this chapter. The steam tables should be studied very carefully, as anyone working problems relating to steam will be using them constantly, and considerable study is required to become proficient in their use.

It will be noted that the steam table is headed "Properties of Dry Saturated Steam," and the question naturally arises, What is meant by *saturated* steam? By saturated steam is meant steam that is at the evaporating temperature corresponding to its pressure. As steam is formed in a boiler and rises from the

surface of the water, it is saturated and will remain so as long as it is in contact with water. So long as steam is in a boiler or in close communication with water it cannot be otherwise than saturated steam. Any attempt to heat the steam to a higher temperature will fail as it will merely transmit the heat to the water and cause further evaporation. Steam may, however, be removed from the presence of water and heated to a higher temperature. It would then be *superheated steam.* Whenever steam is mentioned without any qualifying word, *saturated* steam is meant. If the steam is superheated, it is spoken of as *superheated* steam.

Saturated steam may be either *dry* or *wet.* Dry steam is as clear and transparent as air and is not visible. The steam which we see in the exhaust from an engine or rising from pipes on the roofs of buildings is wet steam, and the visible part consists of small particles of water, or condensed steam. Do not get the idea that saturated steam necessarily means wet steam. Saturated steam may be perfectly dry. One may show this clearly by partially filling a small glass bottle with water and placing it, loosely corked, on a stove. When the water boils, no mist is seen such as we usually imagine to be the appearance of steam. The bottle will remain perfectly transparent just as if filled with air. Steam is visible only when it is wet and contains small particles of water suspended in it just as water is suspended in air during a fog. When a boiler is blown off, or when a whistle is blown, it will be noticed that the steam is not visible until it is about 3 or 4 inches from the end of the pipe where some of it has been condensed by the colder air.

66. Pressure.—The properties of steam depend upon the absolute pressure under which it is formed; consequently the absolute pressure is the first item given in the steam tables. The pressure offers a certain resistance to the expansion of water into steam, and it is the amount of this resistance that determines the temperature of evaporation and other quantities.

In case only the gage pressure is known, the steam table may be used by adding 14.7 lb. to the gage pressure in order to obtain the absolute pressure, and the absolute pressure obtained in this way used for finding quantities in the steam table. If, however, the barometer reading is known in addition to the gage pressure, it is best to determine the actual absolute pressure by adding the barometer pressure to the gage pressure. In finding properties

of steam at pressures below atmospheric, it is especially desirable to calculate the absolute pressure from barometer and vacuum gage readings. An example will show readily what a difference this may make:

Suppose a vacuum gage on a condenser shows a vacuum of 27 in. and we want to find the temperature at which the steam is condensing. Without knowing the barometer reading we would say that

$$27 \times .4908 = 13.25$$

and that at a vacuum of 13.25 lb. (-13.25 lb. gage), which corresponds to an absolute pressure of 1.45 lb. per sq. in., water boils or condenses at about 115°. This assumes that the barometer reading is 29.92 inches.

Now, suppose that we first look at a barometer and find that it stands at only 28 in. Our condenser has more vacuum than we thought it had. The absolute pressure in the condenser is

$$(28-27) \times .4908 = .4908 \text{ lb. per sq. in.}$$

or not quite .5 lb. per sq. in. absolute, and we find that the temperature of the steam and water in the condenser is a little less than 79° F., instead of being 115°.

67. Temperature of Evaporation.—The second column of the steam table gives the temperatures, t, at which water evaporates when under the absolute pressures given in the first column. These temperatures are also the temperatures of saturated steam at the given pressures, and are likewise the temperatures at which steam under the given pressures will condense.

When water is heated in an open vessel under atmospheric pressure (14.7 lb. per sq. in. absolute) it boils at 212° F. If the pressure is reduced, the resistance to the formation of steam is diminished and boiling takes place at a lower temperature. For example, in a vacuum of 28 inches (.946 lb. per sq. in. absolute) water will boil at about 100° F., and, if the absolute pressure is reduced to .0886 lb. per sq. in., water will boil at 32° F., its freezing point under atmospheric pressure. On the other hand, if water is under a pressure greater than that of the atmosphere, its temperature must be raised above 212° F. before it will boil. This is the condition which usually exists in a steam boiler. If the pressure in the boiler is 144 lb. per sq. in. absolute (129.3 lb. gage), the temperature of both the water and the steam in the

boiler is 355.3° F. Since there is a different boiling temperature for each pressure, a thermometer placed in a boiler would serve as a pressure gage, but perhaps would not be as convenient for the fireman.

It will be observed from the steam table that in all cases the boiling temperature increases as the pressure increases, and decreases as the pressure decreases. This fact may be illustrated by the following interesting experiment: A glass flask or bottle, as shown in Fig. 57, is partly filled with water and placed over a small gas flame, until the water boils. A tightly fitting stopper is then placed in the neck of the flask to prevent the escape of steam. The flask is then removed from the gas flame as shown

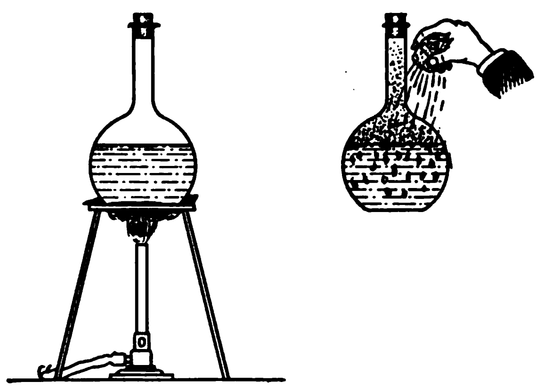

Fig. 57.

in Fig. 57. The temperature will fall rapidly below the boiling point, but if cold water is poured over the flask, the water will begin to boil vigorously. The cold water condenses the steam in the flask, thus lowering the pressure and enabling the water to boil at a temperature below 212° F. The boiling will stop, however, as soon as enough vapor has been formed to restore the pressure. The water may be caused to boil many times without additional heating by simply pouring on more cold water. It is interesting to know that at some places located at high altitudes it is difficult to cook foods by boiling because at these places the atmospheric pressure is much below 14.7 lb. per sq. in. and the temperature at which water boils is considerably below 212° F.

68. Heat of the Liquid.—The heat of the liquid, *h*, per pound

of water is given for various pressures in the third column of the steam table. Approximately, the value of the heat of the liquid per pound is the difference between the boiling temperature and 32° F., since the specific heat of water is about one. Written as a formula

$$h=(t-32)$$

in which h is the heat of the liquid and t is the boiling temperature. For rough calculations this is close enough, but for accurate work the value of the heat of the liquid should be obtained from the steam table, since the specific heat of water is not exactly the same at all temperatures. It will be noted that the heat of the liquid at atmospheric pressure (14.7 lb. per sq. in.) as given in the steam table is 180 B.T.U., which is the same as

$$212°-32°=180°$$

At a pressure of 150 lb. per sq. in. the heat of the liquid is 330.2 B.T.U., while the formula

$$h=t-32$$

gives a value of

$$358.5-32=326.5$$

or 5.7 B.T.U. less than its actual value.

69. Latent Heat of Evaporation.—After water has been heated to the boiling point, more heat must be applied to change it into steam. This heat is called the *latent heat of evaporation* or simply the *latent heat.* The latent heat, L, for one pound of steam, which is the number of heat units that must be supplied to one pound of water at the boiling point to change it into steam, is given in the fourth column of the steam table. The whole amount of the latent heat will be absorbed only when the whole pound of water has been evaporated. When one-quarter of the latent heat has been absorbed, one-quarter of a pound of water will be changed into steam; when one-half of the latent heat has been absorbed, one-half of a pound of water will be changed into steam; and when the whole latent heat has been absorbed the whole pound of water will be changed into steam.

Unlike the other properties of steam so far considered, the latent heat decreases as the pressure increases. At 32° F., the latent heat is 1073.4, the same as the total heat, since there is

no heat of the liquid if the water boils at this temperature. It seems almost incredible that steam can be formed at 32° F., the freezing point of water, but such is the case. It can be done, however, only in a very high vacuum (.0886 lb. per sq. in. absolute pressure), when the resistance to the expansion of water into steam is practically all removed. Under such conditions it is possible to have steam rising directly from a block of ice. At atmospheric pressure the latent heat per pound is 970.4 B.T.U. and at 150 lb. per sq. in. absolute pressure it is 863.2 B.T.U. per pound, decreasing as the pressure increases.

It must be firmly impressed on the mind that the addition of the latent heat of evaporation and the consequent change of water into steam has no effect on the temperature, the steam, when formed, being at the same temperature as the water.

70. Total Heat.—The total heat, H, required to form a pound of steam, is the sum of the heat of the liquid per pound and the latent heat per pound, or

$$H = h + L$$

This quantity is given in the fifth column of the steam table.

While the total heat increases as the pressure increases, the change is small for even a large change of pressure. There is a difference of only 43 B.T.U. between the total heat of steam at atmospheric pressure and at a pressure of 150 lb. per sq. in. absolute. The small increase in the total heat is due to the fact that the latent heat decreases and the heat of the liquid increases as the pressure increases.

71. Volume.—The volume of steam as given in steam tables is the number of cubic feet of space occupied by one pound of steam. Steam occupies much more space than the water from which it was formed. Thus one pound of water occupies a space of $\frac{1}{62.4} = .016$ cu. ft. while one pound of steam at atmospheric pressure occupies a space of 26.79 cu. ft. which is $\frac{26.79}{.016} = 1674$ times the space which the water occupies. The volume of one pound of steam is given in the sixth column of the steam table, and it will be observed that this quantity decreases as the pressure increases. This is to be expected since a greater pressure compresses any gaseous substance into a smaller space.

72. Density.—The density of steam is the weight of one cubic foot of it; it is therefore the reciprocal of the volume, or

$$\text{density} = \frac{1}{\text{volume}}$$

Some steam tables do not give both the density and volume, since they are so closely related. The densities of steam, as shown by the seventh column of the steam table, increase as the pressure increases.

73. Interpolation from Tables.—Interpolation refers to the method of finding values *between* those given in the tables, as for example, finding the latent heat at 44½ lb. per sq. in. pressure. The table gives L for 44 lb. and for 45 lb., but not for 44½ lb., and we *interpolate* to get this value, which would be half way between 929.2 and 928.2, or just 928.7. Suppose we wish to find the heat of the liquid for 120 lb. gage pressure, which is $120+14.7=134.7$ lb. absolute. The table gives 134 lb. and 135 lb., the corresponding values of h being 321.1 and 321.7. For 1 lb. change in pressure h changes .6. Now, 134.7 lb. is .7 more than 134 lb., or .3 lb. less than 135 lb. We can, therefore, add .7 of .6 to 321.1, or subtract .3 of .6 from 321.7. Either way we get 321.52 as the value of h at 120 lb. gage pressure.

In interpolating, remember that L and v decrease as the pressure increases, and that all other items in the table increase. For most calculations it is sufficiently accurate to take the nearest value given in the table without bothering to interpolate.

74. Properties of Other Vapors.—The preceding parts of this chapter have dealt only with the properties of water and its vapor, steam. Other substances have properties similar in all respects to those of steam, except as to quantity. The most important of these substances are ammonia, carbon dioxide, and sulphur dioxide, and these substances are important because they are used in refrigeration and cold storage work.

All of these substances act in a similar manner to water, existing in the form of a liquid under certain conditions of temperature and pressure, and in the form of a vapor under certain other conditions of temperature and pressure. With each of these substances there is a definite boiling temperature for each different pressure. The relation between pressure and boiling temperature is important in substances used in refrigerating work because this relation determines their suitability for producing low tempera-

tures. For example, a temperature as low as 0° F. may be produced with ammonia by reducing its pressure to about 30 lb. per sq. in. absolute. Low temperatures may therefore be produced with ammonia without using pressures which are difficult to produce. Water, on the other hand, is not suitable for this purpose because a pressure of .0886 lb. per sq. in. absolute would have to be produced in order to obtain a temperature of only 32° F., and this low pressure would be extremely difficult to produce and maintain. The suitability of ammonia, carbon dioxide and sulphur dioxide will be considered more fully in Chapter XV on "Refrigeration."

The refrigerating substances mentioned above also act in a similar manner to water when heat is applied to them. When they are in the form of liquids and are heated the temperature of the liquid first increases until the boiling point for that pressure is reached. Further heating causes boiling and the formation of vapor. While the substance is boiling, the temperature remains constant and the heat absorbed is in the form of latent heat of evaporation. The boiling point and heat of the liquid of these substances increase with the pressure while the latent heat and volume decrease.

In refrigerating work the temperature and latent heat are the two most important properties, hence the tables giving the properties of ammonia, carbon dioxide, and sulphur dioxide give these quantities a prominent place. The latent heat of evaporation is important because, in refrigeration, heat is transferred by the alternate evaporation and condensation of the refrigerating medium and this involves the latent heat.

The heat of the liquid is not given in some tables because the temperature at which the substance is used is often below 32° F., from which temperature the heat of the liquid is calculated, hence this would involve using a negative quantity. When it is desired to know the amount of heat used in heating or cooling the liquid, the range of temperature may be multiplied by the specific heat of the liquid, and this product used instead of the heat of the liquid. In problems relating to ammonia the specific heat of the liquid may be taken as 1.057. Ammonia is the most commonly used refrigerating medium; hence its properties are given more fully than those for either carbon dioxide or sulphur dioxide.

PROPERTIES OF SATURATED AMMONIA

(Goodenough-Mosher)

Absolute pressure, lb. per sq. in.	Temperature, degrees Fahr.	Latent heat of vaporization, B.T.U.	Weight per cu. ft. of vapor in pounds
10	−40.4	602.2	.0388
14	−28.9	593.9	.0532
18	−19.8	587.2	.0675
22	−12.2	581.2	.0815
26	− 5.7	576.6	.0953
30	.1	572.1	.1090
34	5.3	568.1	.1226
38	10.0	564.4	.1362
42	14.4	560.9	.1500
46	18.4	557.6	.1634
50	22.1	554.6	.1765
54	25.6	551.7	.1896
60	30.5	547.7	.2097
64	33.6	545.1	.2229
68	36.5	542.6	.2360
72	39.3	540.2	.2494
76	42.0	537.9	.2624
80	44.5	535.8	.2753
84	47.0	533.6	.2884
88	49.4	531.5	.3017
92	51.7	529.5	.3144
96	53.9	527.5	.3278
100	56.0	525.6	.3406
104	58.1	523.7	.3535
108	60.1	521.9	.3667
112	62.1	520.1	.3798
116	64.0	518.4	.3927
120	65.8	516.7	.4056
124	67.7	515.0	.4185
128	69.5	513.3	.4316
132	71.2	511.7	.4447
136	72.9	510.1	.4577
140	74.5	508.6	.4708
144	76.2	507.0	.4835
148	77.7	505.6	.4963
152	79.3	504.0	.5092
156	80.8	502.6	.5220
160	82.3	501.1	.5353
164	83.8	499.7	.5483
168	85.2	498.3	.5609
172	86.6	496.9	.5738
176	88.0	495.5	.5869
180	89.4	494.1	.6000
184	90.7	492.8	.6135
188	92.1	491.5	.6266
192	93.4	490.1	.6395
196	94.6	488.9	.6524
200	95.9	[illegible]	.6650

PROPERTIES OF SATURATED CARBON DIOXIDE

Temperature, degrees Fahr.	Absolute pressure, lb. per sq. in.	Heat of liquid above 32° F., B.T.U.	Latent heat of vaporization, B.T.U.	Volume of one pound, cu. ft.
−4	288.7	−17.19	117.6	.312
14	385.4	− 9.00	110.7	.229
32	503.5	.00	99.8	.167
50	650.1	10.28	86.0	.120
68	826.4	23.08	66.5	.083
86	1040.0	45.45	27.1	.048
104	....	....	....	....

PROPERTIES OF SATURATED SULPHUR DIOXIDE

Temperature, degrees Fahr.	Absolute pressure, lb. per sq. in.	Heat of liquid above 32° F., B.T.U.	Latent heat of vaporization, B.T.U.	Volume of one pound cu. ft.
−4	9.27	−11.16	171.0	8.06
14	14.75	− 5.69	168.2	5.27
32	22.53	.00	164.2	3.59
50	33.26	5.90	158.9	2.44
68	47.61	12.03	152.5	1.71
86	66.36	18.34	144.8	1.22
104	90.30	24.88	135.9	.88

PROPERTIES OF DRY SATURATED STEAM

Reproduced by permission from "Steam Tables and Diagrams," by L. S. Marks and H. N. Davis.

1 Absolute pressure, lb. per sq. in. *p*	2 Temperature, degrees Fahr. *t*	3 Heat of the liquid per lb., B.T.U. *h*	4 Latent heat of evaporation per lb., B.T.U. *L*	5 Total heat per pound, B.T.U. *H*	6 Volume of 1 lb., cu. ft. *v*	7 Density or weight of 1 cu. ft., lbs. *d*
.0886	32.0	0.0	1073.4	1073.4	329.4	.000304
1	101.83	69.8	1034.6	1104.4	333.0	.00300
2	126.15	94.0	1021.0	1115.0	173.5	.00576
3	141.52	109.4	1012.3	1121.6	118.5	.00845
4	153.01	120.9	1005.7	1126.5	90.5	.01107
5	162.28	130.1	1000.3	1130.5	73.33	.01364
6	170.06	137.9	995.8	1133.7	61.89	.01616
7	176.85	144.7	991.8	1136.5	53.56	.01867
8	182.86	150.8	988.2	1139.0	47.27	.02115
9	188.27	156.2	985.0	1141.1	42.36	.02361
10	193.22	161.1	982.0	1143.1	38.38	.02606
11	197.75	165.7	979.2	1144.9	35.10	.02849
12	201.96	169.9	976.6	1146.5	32.36	.03090
13	205.87	173.8	974.2	1148.0	30.03	.03330
14	209.55	177.5	971.9	1149.4	28.02	.03569
14.7	212.00	180.0	970.4	1150.4	26.79	.03732
15	213.0	181.0	969.7	1150.7	26.27	.03806
16	216.3	184.4	967.6	1152.0	24.79	.04042
17	219.4	187.5	965.6	1153.1	23.38	.04277
18	222.4	190.5	963.7	1154.2	22.16	.04512
19	225.2	193.4	961.8	1155.2	21.07	.04746
20	228.0	196.1	960.0	1156.2	20.08	.04980
21	230.6	198.8	958.3	1157.1	19.18	.05213
22	233.1	201.3	956.7	1158.0	18.37	.05445
23	235.5	203.8	955.1	1158.8	17.62	.05676
24	237.8	206.1	953.5	1159.6	16.93	.05907
25	240.1	208.4	952.0	1160.4	16.30	.0614
26	242.2	210.6	950.6	1161.2	15.72	.0636
27	244.4	212.7	949.2	1161.9	15.18	.0659
28	246.4	214.8	947.8	1162.6	14.67	.0682
29	248.4	216.8	946.4	1163.2	14.19	.0705

1 Absolute pressure, lb. per sq. in. p	2 Temperature, degrees Fahr. t	3 Heat of the liquid per lb., B.T.U. h	4 Latent heat of evaporation per lb., B.T.U. L	5 Total heat per lb., B.T.U. H	6 Volume of 1 lb., cu. ft. v	7 Density or weight of 1 cu. ft., lbs. d
30	250.3	218.8	945.1	1163.9	13.74	.0728
31	252.2	220.7	943.8	1164.5	13.32	.0751
32	254.1	222.6	942.5	1165.1	12.93	.0773
33	255.8	224.4	941.3	1165.7	12.57	.0795
34	257.6	226.2	940.1	1166.3	12.22	.0818
35	259.3	227.9	938.9	1166.8	11.89	.0841
36	261.0	229.6	937.7	1167.3	11.58	.0863
37	262.6	231.3	936.6	1167.8	11.29	.0886
38	264.2	232.9	935.5	1168.4	11.01	.0908
39	265.8	234.5	934.4	1168.9	10.74	.0931
40	267.3	236.1	933.3	1169.4	10.49	.0953
41	268.7	237.6	932.2	1169.8	10.25	.0976
42	270.2	239.1	931.2	1170.3	10.02	.0998
43	271.7	240.5	930.2	1170.7	9.80	.1020
44	273.1	242.0	929.2	1171.2	9.59	.1043
45	274.5	243.4	928.2	1171.6	9.39	.1065
46	275.8	244.8	927.2	1172.0	9.20	.1087
47	277.2	246.1	926.3	1172.4	9.02	.1109
48	278.5	247.5	925.3	1172.8	8.84	.1131
49	279.8	248.8	924.4	1173.2	8.67	.1153
50	281.0	250.1	923.5	1173.6	8.51	.1175
51	282.3	251.4	922.6	1174.0	8.35	.1197
52	283.5	252.6	921.7	1174.3	8.20	.1219
53	284.7	253.9	920.8	1174.7	8.05	.1241
54	285.9	255.1	919.9	1175.0	7.91	.1263
55	287.1	256.3	919.0	1175.4	7.78	.1285
56	288.2	257.5	918.2	1175.7	7.65	.1307
57	289.4	258.7	917.4	1176.0	7.52	.1329
58	290.5	259.8	916.5	1176.4	7.40	.1350
59	291.6	261.0	915.7	1176.7	7.28	.1372
60	292.7	262.1	914.9	1177.0	7.17	.1394
61	293.8	263.2	914.1	1177.3	7.06	.1416
62	294.9	264.3	913.3	1177.6	6.95	.1438
63	295.9	265.4	912.5	1177.9	6.85	.1460
64	297.0	266.4	911.8	1178.2	6.75	.1482

1 Absolute pressure, lb. per sq. in. p	2 Temperature, degrees Fahr. t	3 Heat of the liquid per lb. B.T.U. h	4 Latent heat of evaporation per lb., B.T.U. L	5 Total heat per lb., B.T.U. H	6 Volume of 1 lb., cu. ft. v	7 Density or weight of one cu. ft., lbs d
65	298.0	267.5	911.0	1178.5	6.65	.1503
66	299.0	268.5	910.2	1178.8	6.56	.1525
67	300.0	269.6	909.5	1179.0	6.47	.1547
68	301.0	270.6	908.7	1179.3	6.38	.1569
69	302.0	271.6	908.0	1179.6	6.29	.1590
70	302.9	272.6	907.2	1179.8	6.20	.1612
71	303.9	273.6	906.5	1180.1	6.12	.1634
72	304.8	274.5	905.8	1180.4	6.04	.1656
73	305.8	275.5	905.1	1180.6	5.96	.1678
74	306.7	276.5	904.4	1180.9	5.89	.1699
75	307.6	277.4	903.7	1181.1	5.81	.1721
76	308.5	278.3	903.0	1181.4	5.74	.1743
77	309.4	279.3	902.3	1181.6	5.67	.1764
78	310.3	280.2	901.7	1181.8	5.60	.1786
79	311.2	281.1	901.0	1182.1	5.54	.1808
80	312.0	282.0	900.3	1182.3	5.47	.1829
81	312.9	282.9	899.7	1182.5	5.41	.1851
82	313.8	283.8	899.0	1182.8	5.34	.1873
83	314.6	284.6	898.4	1183.0	5.28	.1894
84	315.4	285.5	897.7	1183.2	5.22	.1915
85	316.3	286.3	897.1	1183.4	5.16	.1937
86	317.1	287.2	896.4	1183.6	5.10	.1959
87	317.9	288.0	895.8	1183.8	5.05	.1980
88	318.7	288.9	895.2	1184.0	5.00	.2001
89	319.5	289.7	894.6	1184.2	4.94	.2023
90	320.3	290.5	893.9	1184.4	4.89	.2044
91	321.1	291.3	893.3	1184.6	4.84	.2065
92	321.8	292.1	892.7	1184.8	4.79	.2087
93	322.6	292.9	892.1	1185.0	4.74	.2109
94	323.4	293.7	891.5	1185.2	4.69	.2130
95	324.1	294.5	890.9	1185.4	4.65	.2151
96	324.9	295.3	890.3	1185.6	4.60	.2172
97	325.6	296.1	889.7	1185.8	4.56	.2193
98	326.4	296.8	889.2	1186.0	4.51	.2215
99	327.1	297.6	888.6	1186.2	4.47	.2237

1 Absolute pressure, lb. per sq. in. p	2 Temperature, degrees Fahr. t	3 Heat of the liquid per lb., B.T.U. h	4 Latent heat of evaporation per lb., B.T.U. L	5 Total heat per lb., B.T.U. H	6 Volume of 1 lb., cu. ft. v	7 Density or weight of one cu. ft., lbs. d
100	327.8	298.3	888.0	1186.3	4.429	.2258
101	328.6	299.1	887.4	1186.5	4.388	.2279
102	329.3	299.8	886.9	1186.7	4.347	.2300
103	330.0	300.6	886.3	1186.9	4.307	.2322
104	330.7	301.3	885.8	1187.0	4.268	.2343
105	331.4	302.0	885.2	1187.2	4.230	.2365
106	332.0	302.7	884.7	1187.4	4.192	.2336
107	332.7	303.4	884.1	1187.5	4.155	.2408
108	333.4	304.1	883.6	1187.7	4.118	.2429
109	334.1	304.8	883.0	1187.9	4.082	.2450
110	334.8	305.5	882.5	1188.0	4.047	.2472
111	335.4	306.2	881.9	1188.2	4.012	.2593
112	336.1	306.9	881.4	1188.4	3.978	.2514
113	336.8	307.6	880.9	1188.5	3.945	.2535
114	337.4	308.3	880.4	1188.7	3.912	.2556
115	338.1	309.0	879.8	1188.8	3.880	.2577
116	338.7	309.6	879.3	1189.0	3.848	.2599
117	339.4	310.3	878.8	1189.1	3.817	.2620
118	340.0	311.0	878.3	1189.3	3.786	.2641
119	340.6	311.6	877.8	1189.4	3.756	.2662
120	341.3	312.3	877.2	1189.6	3.726	.2683
121	341.9	313.0	876.7	1189.7	3.697	.2705
122	342.5	313.6	876.2	1189.8	3.668	.2726
123	343.2	314.3	875.7	1190.0	3.639	.2748
124	343.8	314.9	875.2	1190.1	3.611	.2769
125	344.4	315.5	874.7	1190.3	3.583	.2791
126	345.0	316.2	874.2	1190.4	3.556	.2812
127	345.6	316.8	873.8	1190.5	3.530	.2833
128	346.2	317.4	873.3	1190.7	3.504	.2854
129	346.8	318.0	872.8	1190.8	3.478	.2875
130	347.4	318.6	872.3	1191.0	3.452	.2897
131	348.0	319.3	871.8	1191.1	3.427	.2918
132	348.5	319.9	871.3	1191.2	3.402	.2939
133	349.1	320.5	870.9	1191.3	3.378	.2960
134	349.7	321.1	870.4	1191.5	3.354	.2981

1 Absolute pressure, lb. per sq. in. p	2 Temperature, degrees Fahr. t	3 Heat of the liquid per lb., B.T.U. h	4 Latent heat of evaporation per lb., B.T.U. L	5 Total heat per lb., B.T.U. H	6 Volume of 1 lb., cu. ft. v	7 Density or weight of one cu. ft., lbs. d
135	350.3	321.7	869.9	1191.6	3.331	.3002
136	350.8	322.3	869.4	1191.7	3.308	.3023
137	351.4	322.8	869.0	1191.8	3.285	.3044
138	352.0	323.4	868.5	1192.0	3.263	.3065
139	352.5	324.0	868.1	1192.1	3.241	.3086
140	353.1	324.6	867.6	1192.2	3.219	.3107
141	353.6	325.2	867.2	1192.3	3.197	.3129
142	354.2	325.8	866.7	1192.5	3.175	.3150
143	354.7	326.3	866.3	1192.6	3.154	.3171
144	355.3	326.9	865.8	1192.7	3.133	.3192
145	355.8	327.4	865.4	1192.8	3.112	.3213
146	356.3	328.0	864.9	1192.9	3.092	.3234
147	356.9	328.6	864.5	1193.0	3.072	.3255
148	357.4	329.1	864.0	1193.2	3.052	.3276
149	357.9	329.7	863.6	1193.3	3.033	.3297
150	358.5	330.2	863.2	1193.4	3.012	.3320
151	359.0	330.8	862.7	1193.5	2.993	.3341
152	359.5	331.4	862.3	1193.6	2.974	.3362
153	360.0	331.9	861.8	1193.7	2.956	.3383
154	360.5	332.4	861.4	1193.8	2.938	.3404
155	361.0	332.9	861.0	1194.0	2.920	.3425
156	361.6	333.5	860.6	1194.1	2.902	.3446
157	362.1	334.0	860.1	1194.2	2.885	.3467
158	362.6	334.6	859.7	1194.3	2.868	.3488
159	363.1	335.0	859.3	1194.4	2.851	.3508
160	363.6	335.6	858.8	1194.5	2.834	.3529
161	364.1	336.2	858.4	1194.6	2.818	.3549
162	364.6	336.7	858.0	1194.7	2.801	.3570
163	365.1	337.2	857.6	1194.8	2.785	.3591
164	365.6	337.7	857.2	1194.9	2.769	.3612
165	366.0	338.2	856.8	1195.0	2.753	.3633
166	366.5	338.7	856.4	1195.1	2.737	.3654
167	367.0	339.2	855.9	1195.2	2.721	.3675
168	367.5	339.7	855.5	1195.3	2.706	.3696
169	368.0	340.2	855.1	1195.4	2.690	.3717

1 Absolute pressure, lb. per sq. in. p	2 Temperature, degrees Fahr. t	3 Heat of the liquid per lb., B.T.U. h	4 Latent heat of evaporation per lb., B.T.U. L	5 Total heat per lb., B.T.U. H	6 Volume of 1 lb., cu. ft. v	7 Density or weight of one cu. ft., lbs. d
170	368.5	340.7	854.7	1195.4	2.675	.3738
171	368.9	341.2	854.3	1195.5	2.660	.3759
172	369.4	341.7	853.9	1195.6	2.645	.3780
173	369.9	342.2	853.5	1195.7	2.631	.3801
174	370.4	342.7	853.1	1195.8	2.616	.3822
175	370.8	343.2	852.7	1195.9	2.602	.3843
176	371.3	343.7	852.3	1196.0	2.588	.3864
177	371.7	344.2	851.9	1196.1	2.574	.3885
178	372.2	344.7	851.5	1196.2	2.560	.3906
179	372.7	345.2	851.2	1196.3	2.547	.3927
180	373.1	345.6	850.8	1196.4	2.533	.3948
181	373.6	346.1	850.4	1196.5	2.520	.3969
182	374.0	346.6	850.0	1196.6	2.507	.3989
183	374.5	347.1	849.6	1196.7	2.494	.4010
184	374.9	347.6	849.2	1196.8	2.481	.4031
185	375.4	348.0	848.8	1196.8	2.468	.4052
186	375.8	348.5	848.4	1196.9	2.455	.4073
187	376.3	349.0	848.0	1197.0	2.443	.4094
188	376.7	349.4	847.7	1197.1	2.430	.4115
189	377.2	349.9	847.3	1197.2	2.418	.4136
190	377.6	350.4	846.9	1197.3	2.406	.4157
191	378.0	350.8	846.5	1197.3	2.393	.4178
192	378.5	351.3	846.1	1197.4	2.381	.4199
193	378.9	351.7	845.8	1197.5	2.369	.4220
194	379.3	352.2	845.4	1197.6	2.358	.4241
195	379.8	352.7	845.0	1197.7	2.346	.4262
196	380.2	353.1	844.7	1197.8	2.335	.4283
197	380.6	353.6	844.3	1197.8	2.323	.4304
198	381.0	354.0	843.9	1197.9	2.312	.4325
199	381.4	354.4	843.6	1198.0	2.301	.4346
200	381.9	354.9	843.2	1198.1	2.290	.437
205	384.0	357.1	841.4	1198.5	2.237	.447
210	386.0	359.2	839.6	1198.8	2.187	.457
215	388.0	361.4	837.9	1199.2	2.138	.468
220	389.9	363.4	836.2	1199.6	2.091	.478

1 Absolute pressure, lb. per sq. in. p	2 Temperature, degrees Fahr. t	3 Heat of the liquid per lb., B.T.U. h	4 Latent heat of evaporation per lb., B.T.U. L	5 Total heat per lb., B.T.U. H	6 Volume of 1 lb., cu. ft. v	7 Density or weight of one cu. ft., lbs. d
225	391.9	365.5	834.4	1199.9	2.046	.489
230	393.8	367.5	832.8	1200.2	2.004	.499
235	395.6	369.4	831.1	1200.6	1.964	.509
240	397.4	371.4	829.5	1200.9	1.924	.520
245	399.3	373.3	827.9	1201.2	1.887	.530
250	401.1	375.2	826.3	1201.5	1.850	.541
260	404.5	378.9	823.1	1202.1	1.782	.561
270	407.9	382.5	820.1	1202.6	1.718	.582
280	411.2	386.0	817.1	1203.1	1.658	.603
290	414.4	389.4	814.2	1203.6	1.602	.624
300	417.5	392.7	811.3	1204.1	1.551	.645

QUESTIONS

88. What is the difference between saturated and superheated steam?

89. What is meant by the heat of the liquid of steam? What is meant by the latent heat?

90. It is said that eggs cannot be hard-boiled on top of Pikes' Peak, which is about 14,000 feet above sea level. Explain.

91. A steam boiler carries a pressure of 120 lb. per sq. in. absolute and water enters it at a temperature of 100°. How many heat units are expended in heating each pound of water from this temperature to the boiling point?

92. A boiler horse-power is defined as the evaporation of 34½ pounds of water per hour at 212° F. How many heat units are required to develop one boiler horse-power?

93. How many foot-pounds is one boiler horse-power equivalent to?

94. A number of years ago a boiler horse-power was defined as the evaporation of 30 pounds of water per hour at a temperature of 100° F. into steam at 70 lb. gage pressure. How much difference is there between the horse-power defined in this way and as defined in Question 92?

95. A boiler carrying 150 lb. per sq. in. absolute pressure receives its feed water at a temperature of 190° F. This boiler is fired with coal having a heating value of 13,000 B.T.U. per pound and 9 pounds of water are evaporated for each pound of coal fired. What per cent. of the heat energy in the coal goes into steam?

96. If a certain kind of coal has a heating value of 12,500 B.T.U. per pound and contains 6% of moisture what per cent. of the heat energy in the coal must be utilized in evaporating the moisture? (Assume temperature of coal as 60° F.)

97. A boiler carrying 120 lb. per sq. in. gage pressure receives feed water at 140° F. and generates 8 lb. of steam per pound of coal fired, the coal having a heating value of 12,000 B.T.U. If this coal costs $2.50 per ton of 2000 lbs., find the cost of generating 1000 pounds of steam.

CHAPTER X

CONDENSATION AND EVAPORATION

75. Condensation.—Condensation is the opposite of evaporation. In evaporation, a liquid is changed into a vapor; in condensation, a vapor is changed into a liquid. A liquid absorbs heat in evaporating; a vapor gives up heat in condensing to a liquid. The amount of heat and the temperatures involved in both cases are the same for the same pressures, the only difference being that evaporation is a result of heating, while condensation is a result of cooling.

It is customary to consider condensation as referring to steam, but it should be remembered that other substances such as ammonia, carbon dioxide, and sulphur dioxide act in a similar manner, the only difference being that for the same pressures, the temperatures and quantities of heat transferred are different.

The boiling point of water at atmospheric pressure is 212°F. If one pound of water at a temperature of 212° F., and at atmospheric pressure, be supplied with 970.4 B.T.U. (its latent heat) it will change into steam having a temperature of 212° F. If the pound of steam thus formed is cooled so that 970.4 B.T.U. are taken from it, it will change back into water, or will condense, and the water resulting from the condensation will have a temperature of 212° F. The process of condensation refers only to the change of vapor into liquid and, therefore, the heat of the liquid is not involved. If the liquid resulting from condensation is cooled, the quantity of heat taken from it will just equal the amount supplied in heating it through the same range of temperature, provided there is no loss of heat in either case.

The only quantity of heat involved in condensation is the latent heat of vaporization, the latent heat being absorbed when a vapor changes into a liquid. Moreover, the whole pound of vapor will be condensed only when the whole latent heat of one pound is extracted from the vapor. In the example mentioned above, if only one-half of the latent heat (485.2 B.T.U.) is extracted from the steam only one-half of a pound of it will

condense, and if only one-quarter of the latent heat (247.6 B.T.U.) is extracted only one-quarter of a pound of it will condense.

Any saturated vapor such as steam has the same temperature as the boiling liquid from which it is formed; hence any attempt to cool it will result in taking heat from the vapor and the condensation of a portion of it, but will not affect its temperature unless the pressure is changed. If, however, the vapor is taken away from the presence of the liquid from which it is formed and its pressure changed, its temperature will also change; hence it will condense at the boiling point corresponding to the new pressure. To illustrate this, suppose saturated steam enters the cylinder of a steam engine at an absolute pressure of 125 lb. per sq. in. Its temperature will then be 344.4° F. and if it comes in contact with any surfaces at a lower temperature than this some of it will condense, the water resulting from the condensation having a temperature of 344.4° F. As the pressure of the steam

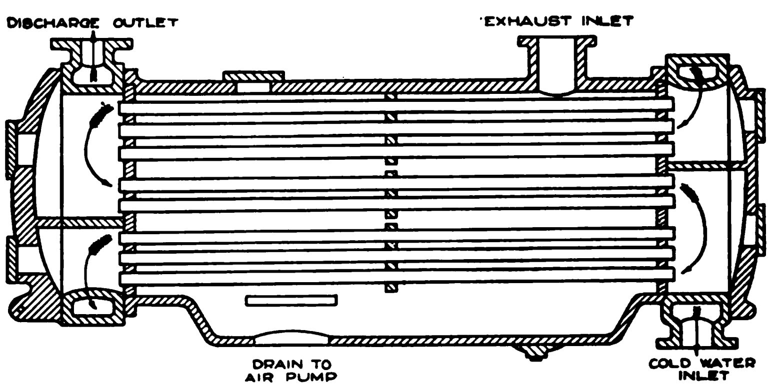

FIG. 58. Steam condenser.

is reduced by expansion its temperature is also reduced. Suppose the pressure at the end of expansion is 20 lb. per sq. in. absolute, its temperature will then be 228° F., and it may be condensed by bringing it in contact with surfaces having a lower temperature. The water resulting from its condensation at 20 lb. per sq. in. will have a temperature of 228° F., the same temperature as the steam at this pressure.

In engineering work steam (or any other vapor), is condensed by passing it into vessels such as shown in Fig. 58, in which it comes in contact with the surface of pipes through which comparatively

cold water is circulating. The water absorbs heat from the steam and condenses it and by maintaining a flow of water the cooling surfaces are prevented from becoming hot. An apparatus for condensing vapors is called a condenser. Condensers for steam are sometimes arranged so that water is sprayed into the steam as it enters the condenser, thus cooling and condensing it. This mixes the condensed steam with the condensing water however, which, in some cases, may be undesirable.

A vapor, especially at low pressures, occupies many times more space than the liquid from which it was formed; hence, when the vapor is condensed, the space which it occupied is left vacant and a high degree of vacuum is produced. In steam power plants the exhaust steam is passed into condensers where a partial vacuum is maintained by its condensation. This reduces the back pressure on the piston and permits the engine to develop more power. The vacuum will be more complete the faster the steam is condensed. If the steam is not condensed as fast as it is supplied to the condenser, the accumulation of steam increases the pressure in the condenser and destroys the vacuum.

The degree of vacuum produced by a condensor will depend upon the amount of condensing water supplied and upon its temperature. The absorption of the latent heat of the steam by the condensing water increases its temperature. Therefore sufficient water must be supplied so that its temperature will not increase to that of the steam because, if it did, the steam would not be condensed.

76. Evaporation by Reduced Pressure.—In the preceding chapter an experiment was described which shows that water may be boiled without the application of heat by reducing the pressure upon the surface of the water. In this experiment an open flask containing water is heated until the water boils, after which it is tightly corked and removed from the gas jet used in heating it. As soon as the flask is removed from the gas jet, boiling ceases. If now cold water be poured over the flask the water in the flask begins to boil violently. The explanation of this peculiar action of the water in the flask is as follows:—The space above the water is filled with steam. The water is at the same temperature as the boiling point corresponding to the pressure of the steam. Pouring cold water on the outside of the flask condenses the steam and reduces the pressure inside the flask. This lowers the boiling point below the actual temperature of the water, thus

causing the water to boil. The boiling will continue until the steam formed raises the pressure to that corresponding to the temperature of the water. This may be made plain by using figures for the pressures and temperatures involved. Suppose that when the flask is removed from the flame the pressure of the steam is 15 lb. per sq. in. absolute. The temperature of the water will be 213° F. Suppose further that when cold water is poured on the flask, the condensation of the steam reduces the pressure in the flask to 2 lb. per sq. in. The boiling temperature corresponding to this pressure is 126.15° F. The water in the flask, having a temperature of 213° F. will be considerably above the boiling point, hence will boil violently until the pressure in the flask is increased.

An amount of heat equal to the latent heat must always be absorbed when water changes into steam; hence, in the above experiment there must be a supply of heat to enable the water to boil. In this case the latent heat required when the water boils is absorbed from the water itself, which has a temperature considerably above the boiling point and is therefore capable of giving up some heat, but, of course, taking heat from the water lowers its temperature, so that its temperature will not be as high after boiling occurs as it was before. In all cases, an amount of heat equal to the latent heat must be absorbed from some source before boiling can occur and unless this amount of heat is available, either from the liquid or from some outside source, boiling cannot occur, even though the pressure be reduced.

In the above discussion only the action of water has been considered, but the results would be the same if other liquids such as ammonia, carbon dioxide, or sulphur dioxide were used instead of water, the only difference being that the temperatures, pressures, and amounts of heat involved would be different.

The fact that reducing the pressure upon a liquid produces a tendency to boil or evaporate, and that, when boiling occurs, large amounts of heat are absorbed, thereby cooling the substance which supplies the heat, forms the basis of certain systems of refrigeration or cooling. The most important system of refrigeration based on these principles uses ammonia as the working substance, since the relations of temperature, pressure, and latent heat for this substance are better adapted to the purpose than those of other substances.

The method of producing refrigerating effect by the evaporation

of ammonia is illustrated diagrammatically in Fig. 59. In this illustration *B* represents a tank filled with water which is to be cooled, and which has immersed in it a coil of pipe *C* which is open at one end. *A* is a steel tank containing liquid ammonia under pressure and *D* is a valve to control the flow of ammonia. Suppose the ammonia in the tank *A* is under a absolute pressure of 180 lb. per sq. in. and, from being stored in a room, is at room temperature, about 70° F. It will then be in the form of a liquid because the actual temperature of the ammonia is below the boiling point for 180 lb. pressure. The valve *D* is now opened and the liquid ammonia allowed to flow into the coil. As the coil is open to the atmosphere, the liquid ammonia in the coil will be under about atmospheric pressure, say 16 lb. per sq. in., for which pressure the boiling point of the ammonia is about 25° F. below zero. As the actual temperature of the ammonia is considerably above this (about 70° F.) the ammonia will immediately begin

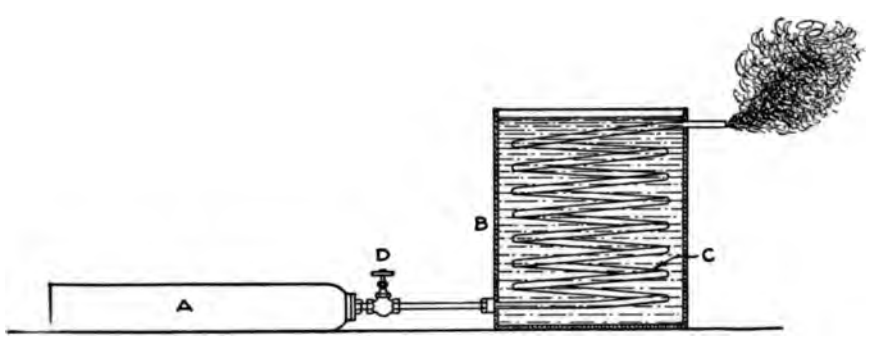

FIG. 59.

to boil provided it can absorb heat. The ammonia absorbs heat from the water surrounding the coil, which is at a higher temperature than the boiling point of the ammonia, and this lowers the temperature of the water. As fast as the ammonia can absorb heat from the water it vaporizes and escapes into the atmosphere. The apparatus shown in Fig. 59 makes up a complete refrigerating system as far as producing low temperatures is concerned. The waste of ammonia vapor into the atmosphere by this system would be objectionable because ammonia is expensive; hence there is included in refrigerating systems an apparatus whose object is to collect the ammonia vapor, compress and condense it,

and return it to the tank A. Refrigerating systems will be more fully treated in Chapter XV.

77. Wet Steam.—When heat is applied slowly to a vessel containing water, the temperature of the water increases slowly until it reaches the boiling point. Small bubbles of steam then begin to form on the surface of the vessel at the points where heat is passing into the water. These small steam bubbles are lighter than the water surrounding them, hence they are detached from the surface of the vessel and rise to the surface of the water. Near the surface of the water they are under less pressure than when at the bottom of the vessel, therefore they expand as they rise through the water and in expanding displace more water, which causes them to rise faster and faster. If the heating is done slowly the bubbles of steam formed will be small and, when they become detached, will rise to the surface slowly. Upon reaching the surface, the bubbles burst and empty their steam into the space above the surface of the water. Steam formed in this manner will be dry saturated steam.

If, on the other hand, heat is supplied to the water so rapidly as to cause it to boil violently, the steam bubbles formed on the heating surface will be large and when they become detached will rise to the surface more rapidly. As the steam bubbles reach the surface they burst violently and the water which forms the film around them is thrown into the steam space in the form of very small particles of water. These particles of water are so small and light that they remain suspended in the mass of steam and cause it to be wet. Thus a boiler may form either dry or wet steam depending upon the rate at which the steam is formed.

The importance of a large disengagement surface for the steam may now be understood. If the disengagement surface is small in proportion to the amount of steam formed, a great many steam bubbles will burst in a small area, keeping the surface of the water in violent commotion and causing more of it to be thrown into the steam. But if the disengagement area is large, a smaller number of steam bubbles will burst in a given area and the surface of the water will not be disturbed very much.

The moisture which is suspended in wet steam is not in the form of vapor since it has not been evaporated, but it still exists in the form of water which is at the temperature of the steam. Wet steam is thus composed of two parts, one of saturated steam and the other of water.

That part of wet steam which is in the form of water has received only enough heat to raise its temperature to the boiling point. If its temperature was originally 32°, it has, therefore, received the "heat of the liquid." That part of the wet steam which is in the form of saturated vapor or steam has received not only enough heat to raise its temperature to the boiling point, but also enough to evaporate it. If the water from which it was formed was originally at 32°, it contains the "total heat" as given in the steam table.

To illustrate the way in which the heat contained in wet steam is divided between the moisture and the steam, consider one pound of wet steam formed under a pressure of 120 lbs. per sq. in. absolute, and suppose the pound of wet steam to consist of $\frac{1}{5}$ or .2 of a pound of moisture and $\frac{4}{5}$ or .8 of a pound of saturated steam. The .2 of a pound of moisture has received enough heat to raise its temperature to the boiling point. If its original temperature was 32°, each pound has received 312.3 B.T.U. which is the heat of the liquid corresponding to a pressure of 120 lbs. per sq. in. absolute. The .2 of a pound of moisture will, therefore, contain $.2 \times 311.9 = 62.46$ B.T.U. The .8 of a pound of saturated steam has received not only enough heat to bring it to the boiling point but also enough to evaporate it. The amount of heat required to bring it to the boiling point is $.8 \times 312.3 = 249.84$ B.T.U. and the amount required to evaporate it will be .8 of the latent heat of one pound or $.8 \times 877.2 = 701.76$ B.T.U. Therefore, the one pound of wet steam contains $62.46 + 249.84 + 701.76 = 1014.06$ B.T.U.

Since the whole pound of water must be heated to the boiling point while only a fraction of the pound has to receive the latent heat of evaporation, the above calculations may be combined into the following formula

$$H_w = h + qL$$

in which H_w is the number of B.T.U. in a pound of wet steam

h is the heat of the liquid

L is the latent heat of evaporation

and q is the fraction of the whole pound which is dry saturated steam

Applying this formula to the above problem

$$H_w = h + qL$$

$$H_w = 312.3 + (.8 \times 877.2)$$

$$= 312.3 + 701.76 = 1014.06 \text{ B.T.U.}$$

which is the same result as obtained before.

Comparing the amount of heat contained in a pound of the wet steam specified above with that contained in a pound of dry steam we see that the wet steam contains only 1014.06 B.T.U. while, if it had been dry, it would contain 1189.6 B.T.U. In other words, the wet steam contains 175.54 less heat units than the dry steam, and the more moisture there is suspended in steam the fewer heat units each pound of the mixture will contain.

Since a pound of wet steam contains less heat than a pound of dry steam, there is a disadvantage in operating a boiler in such manner as to produce wet steam, because a greater weight of steam must be handled in order to transfer a certain number of heat units from the boiler to the engines. This involves larger apparatus and the handling of more feed water. If the amount of moisture in the steam becomes excessive, or the boiler primes, there is danger of flooding the engine cylinder and of damaging the piping by water hammer.

78. Quality of Steam.—The factor q in the above formula for finding the heat contained in wet steam is called the *quality factor*. The quality of steam (sometimes called the dryness of the steam) is the portion of the total weight of steam which is in the form of steam or vapor, as distinguished from that portion which is in the form of moisture. The quality is expressed as a per cent. of the total weight. Thus in the example given above the quality or dryness, q, is .80 or 80%. If one-half of the pound of steam had been water, the other half being in the form of steam, the quality would have been .50 or 50%, and if the steam had contained $\frac{1}{4}$ water and $\frac{3}{4}$ steam its quality would have been .75 or 75%. If the steam had been perfectly dry, all of it would have been in the form of vapor or steam and its quality would, therefore, have been 1.00 or 100%. The wetness of steam is 100 per cent. minus the per cent. of dryness or $100 - q$.

In applying the quality factor to the heat contained in steam it should be remembered that the quality does not apply to the total heat as given in the steam table but only to the latent heat. The heat of the liquid is the same whether the steam is wet or dry but the latent heat in a pound of steam will be less if the steam is wet than

if it is dry. For this reason the formula for the heat in a pound of wet steam must take the form

$$H_w = (h + qL)$$

79. Steam Calorimeters.—The quality of steam may be measured by means of an instrument called a steam calorimeter. There are two forms of steam calorimeters called respectively the *Separating Calorimeter* and the *Throttling Calorimeter*.

80. Separating Calorimeters.—The separating calorimeter shown in cross-section in Fig. 60 separates the water from the steam mechanically, collecting the water at one place and allowing the steam, now free of moisture, to pass off at another. Since water is heavier than an equal volume of steam, if the direction in which a mixture of steam and water is flowing is suddenly changed, the particles of water will be thrown out of the steam. The water, being heavy, tends to continue in a straight line while the steam, being lighter, can have its direction of flow changed more readily. This principle is made use of in the separating calorimeter.

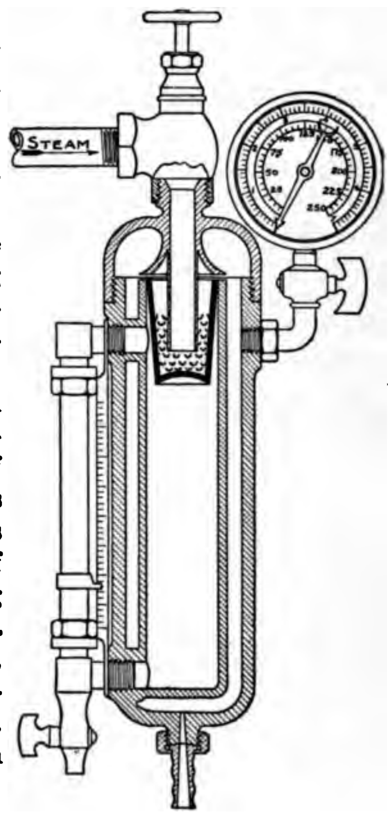

FIG. 60. Separating calorimeter.

The body of the separating calorimeter consists of a double-walled hollow chamber with a steam-pipe connection leading into the inner chamber through the top. A perforated metal basket is suspended in the upper part of the inner chamber, with its bottom a short distance below the end of the steam connection. The bottom of this basket is not perforated. The inner chamber is connected to the outer one through an opening located at the top of the perforated metal basket. The outer chamber, located between the two walls of the body of the calorimeter, has an outlet to the atmosphere through a small hole in the bottom.

In operating the calorimeter, the steam to be tested enters through the tube in the top and discharges against the bottom of the perforated metal basket. The steam, in seeking an outlet, is forced to make a sharp turn as it leaves the tube, thus separating the moisture from it. The steam, which is now dry, passes through the sides of the metal basket and through the opening into the outer chamber. The moisture is separated from the steam and passes through the perforations in the basket, collecting in the bottom of the inner chamber. The amount of water collected in the inner chamber is indicated on a glass gage located outside the body of the calorimeter and connected at top and bottom to the inner chamber. This gage is fitted with a marker which passes over a graduated scale. The scale is usually graduated to read in hundredths of a pound.

The dry steam passes into the outer chamber and out through the opening in the bottom. A gage, resembling a steam gage, is connected to the outer chamber of the calorimeter. The dial of this gage has two sets of graduations, the inner one showing the pressure of the steam in the calorimeter in pounds per square inch above atmospheric pressure, and the other showing the weight of steam flowing through the small opening in the bottom during a period of 10 minutes. The gage is rather unreliable and for this reason it is better to obtain the weight of steam passing through the calorimeter by weighing it. This may be done by connecting a rubber tube to the bottom of the calorimeter and passing the steam into a tub or bucket of cold water, where it will be condensed. By weighing the tub or bucket of water before and after passing the steam into it, its increase in weight may be obtained. This increase in weight represents the weight of dry steam that has passed through the calorimeter.

The calculation of the quality of steam from the readings taken with a separating calorimeter are very simple, since the weight of water and of steam are obtained directly. If W represents the weight of water removed from the steam, as indicated on the glass gage, and W_1 represents the weight of dry steam obtained by condensation in a tub or bucket of water, then the total weight of the wet steam is $W+W_1$ and the quality or dryness will be

$$\frac{W_1}{W+W_1}$$

$$\text{or } q=\frac{W_1}{W+W_1}$$

Example:

Suppose the glass gage shows that the calorimeter has collected .12 lb. of water in a certain time, and during the same time the tub of water has increased in weight 2 lb. $4\frac{1}{2}$ oz. What is the quality of the steam?

Solution:

$$4\tfrac{1}{2}\text{ oz.}=\frac{4.5}{16}=.281\text{ lb.}$$

Therefore, 2 lb. $4\frac{1}{2}$ oz. $=2.281$ lb. $=W_1$

$$q=\frac{W}{W+W_1}=\frac{2.281}{.12+2.281}=\frac{2.281}{2.401}=.95=95\%$$

In this form of calorimeter, radiation from the outer walls, which causes condensation of a portion of the steam, does not affect the accuracy of the results as condensation can take place only in the outer chamber and will, therefore, affect only steam from which the moisture has already been separated.

The separating calorimeter is especially useful in determining the quality of steam which contains considerable moisture. If the quality of the steam is so low that one calorimeter will not remove all the moisture, two calorimeters may be connected so the first one discharges into the second, thus forcing the steam to pass through both. The moisture which passes the first calorimeter will be separated by the second. The separating calorimeter does not give as accurate results as the throttling calorimeter, to be described next, but it can be used with steam having a lower quality.

81. Throttling Calorimeter.—The throttling calorimeter operates on an entirely different principle from that of the separating calorimeter just described. This form of calorimeter takes its name from the fact that the steam, of which the quality is to be determined, is forced to pass through a very small opening, thereby throttling it or causing its pressure to be reduced.

One form of throttling calorimeter is shown in Fig. 61. It consists of a hollow cylindrical shell with a thermometer well extending down its center, and with an opening into the atmosphere at the bottom. Steam is led into the calorimeter through a sampling tube and valve and through a nozzle which has an opening of only about .03 of an inch in diameter. An opening is placed in the shell of the calorimeter directly opposite the nozzle and leading to one branch of a manometer, or glass "U" tube, partly filled with mercury, and provided with a scale divided into inches.

The theory of the operation of a throttling calorimeter is as

follows: The steam drawn from the steam pipe and lead to the nozzle is saturated and under a high pressure. Upon flowing through the nozzle into the chamber of the calorimeter which is open to the atmosphere, the pressure of the steam will be reduced to approximately atmospheric pressure. A study of the steam table will show that high pressure saturated steam contains a greater number of heat units per pound than low pressure saturated steam. The steam taken from the steam pipe cannot gain

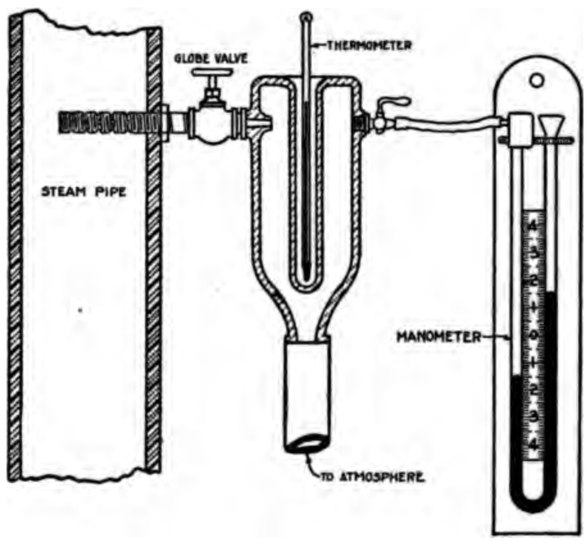

FIG. 61. Throttling calorimeter.

any heat, since there is no source of heat present. Neither can it lose heat except by radiation and, since the calorimeter is small, the small amount of heat lost in this way may be neglected. Therefore, as far as practical results are concerned, the steam in the calorimeter contains as many heat units per pound as the steam in the pipe from which the sample is taken. Since the low pressure steam in the calorimeter requires less heat to saturate it than high pressure steam, there will be more heat in the calorimeter than is required to saturate the steam after its pressure has been reduced. As this excess heat cannot escape, it is absorbed by the steam in the calorimeter thereby raising its temperature, or superheating it. A numerical example will make this plain. Suppose the steam in the main pipe has a pressure of 150 lb. per sq. in. absolute

and a quality of 98%. The number of B.T.U. per pound in this steam will be

$$
\begin{aligned}
\text{B.T.U.} &= h+qL \\
&= 330.2+(.98\times 863.2) \\
&= 330.2+845.94 \\
&= 1176.14
\end{aligned}
$$

and this is the amount of heat which enters the calorimeter per pound of steam. If the steam inside the calorimeter has a pressure of 15 lb. per sq. in. absolute and were merely saturated, it would contain only 1150.7 B.T.U. per pound. Therefore, there will be $1176.14-1150.7=25.44$ B.T.U. inside the calorimeter in excess of that required to saturate the steam, and, as this 25.44 B.T.U. cannot escape, it is absorbed by the steam inside the calorimeter, thereby superheating it.

The readings to be taken for determining the quality of the steam are: first, the pressure of the steam in the pipe from which the sample is taken, for which purpose a steam gage should be attached to the steam pipe; second, the temperature inside the calorimeter as indicated on the thermometer in the well, and third, the pressure inside the calorimeter as indicated by the manometer. The atmospheric pressure as indicated by a barometer should also be read. The readings of pressure and temperature should be taken at the same time.

The method of calculating the quality is illustrated with the following set of readings as taken from the calorimeter:

Gage pressure in steam pipe $=130$ lb. per sq. in.

Temperature in calorimeter $=249.25$

Pressure in calorimeter above atmospheric pressure (manometer reading) $=3$ inches of mercury $=1.47$ lb. per sq. in.

Barometer reading $=28.4$ inches of mercury $=13.94$ lb. per sq. in.

Absolute pressure in steam pipe $=130+13.94=143.94$ lb. per sq. in.

Absolute pressure in calorimeter $=1.47+13.94=15.41$

Heat in one pound of steam in pipe $=h+qL$, the quantities h and L being for a pressure of 143.94 lb. per sq. in.

Heat in calorimeter $=H+.48(t_s-t)$ in which

H = the total heat in one pound of saturated steam at the pressure which exists in the calorimeter

t_s = temperature of the superheated steam in the calorimeter as indicated by the thermoneter

t = temperature of saturated steam at the pressure which exists in the calorimeter.

.48 = specific heat of superheated steam in calorimeter

Now as shown before

$$h+qL=H+.48(t_s-t)$$

$$q=\frac{H+.48\ (t_s-t)-h}{L}$$

$$H=1151.2$$
$$t_s=249.25$$
$$t=214.35$$
$$h=326.86$$
$$L=865.8$$

Therefore,

$$q=\frac{H+.48\ (t_s-t)-h}{L}$$

$$=\frac{1151.2+.48(249.25-214.35)-326.86}{865.8}$$

$$=\frac{1151.2+(.48\times34.9)-326.86}{865.8}$$

$$=\frac{1151.2+16.75-326.86}{865.8}$$

$$=\frac{841.09}{865.8}=.971=97.1\%$$

When the throttling calorimeter is used as directed above, and the quality calculated by the method used in the example, it gives the quality very accurately. It is not suitable, however, for use with steam having a quality less than 96%, as there will not then be enough excess heat in the calorimeter to superheat the steam. The one using a throttling calorimeter may know when it is not superheating the steam by reading the thermometer. If the temperature in the calorimeter is not greater than that corresponding to the temperature of saturated steam at the pressure in the calorimeter, then the steam is not being superheated and the quality cannot be determined by this method. For example, if the thermometer had not indicated a temperature higher than 214.35° F. in the example given above, it would show that the steam was not being superheated and the quality could not have been obtained from these data.

82. Superheated Steam.—If saturated steam is removed from the presence of water and heat is applied to it, its temperature may be raised above that at which it was formed, and this may be done without increasing its pressure. When steam is heated above the boiling temperature corresponding to its pressure it is said to be superheated. The number of degrees by which its actual temperature exceeds that of the boiling point corresponding to the pressure is called the *degrees of superheat* and this term is used to designate the amount of superheat. Thus, if the absolute pressure of the steam is 150 lb. per sq. in. and a thermometer inserted in it shows that its temperature is 465°, then, since the temperature of saturated steam at 150 lb. per sq. in. pressure is 358.5, its degree of superheat is $465-358.5=106.50$. The temperature of saturated steam for any pressure may be found from the steam table while the actual temperature of superheated steam must be measured with a thermometer.

83. Total Heat of Superheated Steam.—Superheated steam contains more heat per pound than saturated steam at the same pressure. The total heat above 32° F. contained in a pound of superheated steam may be found by adding to the total heat of saturated steam for the same pressure, as found in the steam tables, the number of heat units required to superheat the steam. The method formerly used for calculating the number of heat units required to superheat a pound of steam was to multiply the specific heat of superheated steam by the degrees of superheat. Recent investigation shows that the specific heat of superheated steam is different at different temperatures; therefore, this method of determining the number of heat units required to superheat steam is liable to cause serious error unless the average specific heat can be determined.

Within recent years many experiments have been made to determine the number of heat units required to superheat steam. The results of these experiments are shown in the following table. The total heat contained in a pound of superheated steam may be found by adding the values given in this table to the total heat of dry saturated steam as found in a steam table.

The use of this table may be illustrated by the following example: Determine the number of heat units contained in a pound of superheated steam having a pressure of 130 lb. per sq. in. absolute and having a temperature of 447.4° F.

HEAT UNITS REQUIRED TO SUPERHEAT STEAM

Absolute pressure	Degrees of superheat										
	10	20	40	60	80	100	130	160	200	250	300
1	4.5	9.0	18.2	27.3	36.4	45.5	59.2	73.0	91.2	114.1	132.1
10	4.6	9.3	18.6	27.9	37.2	46.4	60.3	74.2	92.9	116.2	139.4
15	4.7	9.4	18.8	28.2	37.6	46.9	60.9	74.9	93.7	117.0	140.4
20	4.7	9.5	19.0	28.4	37.9	47.3	61.5	75.6	94.4	117.9	141.4
30	4.9	9.7	19.4	29.0	38.6	48.2	62.5	76.8	95.8	119.5	143.2
40	4.9	9.9	19.7	29.5	39.3	49.0	63.5	77.8	97.0	120.9	144.7
50	5.1	10.1	20.2	30.2	40.0	49.8	64.5	78.9	98.2	122.2	146.1
60	5.2	10.3	20.5	30.7	40.7	50.6	65.3	79.9	99.4	123.4	147.3
80	5.4	10.7	21.3	31.7	41.9	52.0	66.9	81.7	101.3	125.5	149.6
100	5.7	11.2	22.1	32.8	43.2	53.4	68.4	83.3	103.1	127.3	151.5
130	6.0	11.8	23.1	34.1	44.7	55.1	70.4	85.4	105.2	129.6	153.9
160	6.3	12.5	24.3	35.5	46.3	56.8	72.2	87.3	107.2	131.7	156.1
200	6.9	13.5	25.8	37.4	48.4	59.0	74.4	89.6	109.6	134.3	158.9
250	7.7	14.8	27.8	39.8	50.8	61.5	77.1	92.9	112.4	137.3	162.0
300	8.5	16.1	30.0	42.1	53.3	64.1	79.6	95.0	115.2	140.2	165.1

By referring to the steam table we see that the temperature of saturated steam at 130 lb. pressure is 347.4 and that its total heat is 1191 B.T.U. The degrees of superheat are, therefore, $447.4-347.4=100°$ and the above table shows that for this degree of superheat and for a pressure of 130 lb. the number of heat units required to superheat the steam is 55.1. The pound of superheated steam will, therefore, contain $1191+55.1=1246.1$ B.T.U.

The average specific heat of the superheated steam may be found from the table by dividing the value given in the table by the degrees of superheat. Thus, in the above example, the average specific heat would be

$$\frac{55.1}{100}=.551$$

Since superheated steam contains more heat than dry saturated steam it is evident that the superheated steam is also dry. If superheated steam is passed through a throttling calorimeter, it will show a quality greater than 100%, which indicates simply that the steam was already superheated when it entered the calorimeter.

QUESTIONS

98. What is meant by the quality of steam?

99. Why is wet steam objectionable?

100. What is the cause of a boiler making wet steam?

101. Describe one method of measuring the quality of steam.

102. The water leaving a steam radiator may be at the same temperature as the steam entering the radiator. How, then, is heat given to the room?

103. 6 pounds of wet steam having a quality of 80% and a pressure of 20 pounds per sq. in. absolute are passed into a barrel containing 250 lbs. of water at a temperature of 60° F. What is the resulting temperature of the water?

104. An ammonia compressor delivers compressed ammonia vapor to a condenser which is supplied with cooling water at a temperature of 60° F. What must be the pressure of the ammonia in order that it may be condensed?

105. A pound of ice in melting gives up 142 B.T.U. How many pounds of ammonia having a temperature of 56° F. must be evaporated at a pressure of 42 lb. per sq. in. absolute in order to produce as much cooling effect as would be obtained from the melting of one ton (2000 lb.) of ice?

106. Calculate the quality of steam from the following set of readings obtained from a throttling calorimeter:

Steam pressure 130 lb. per sq. in. gage.
Temperature in calorimeter 261° F.
Pressure in calorimeter 2.5 inches of mercury.
Barometer reading 27.5 inches of mercury.

107. One boiler evaporates 9 lb. of water having a temperature of 120° F. into steam having a pressure of 160 lb. per sq. in. absolute, and a quality of 99% for each pound of coal fired. Another boiler using the same kind of coal, receives feed water at 180° F. and evaporates 9½ lbs. for each pound of coal fired into steam having a pressure of 115 lb. per sq. in. absolute, and a quality of 97%. Which of these two boilers is more efficient?

CHAPTER XI

THE STEAM ENGINE

84. Types of Engines.—Steam engines may be divided conveniently into three types or classes depending upon their types of valve mechanism. These types of engines are the Plain Slide Valve, the Automatic High Speed, and the Corliss engines. Plain slide valve engines and automatic high-speed engines both have slide valves but these engines have different methods of controlling the speed. The Corliss engine is a slow-speed engine and has a different kind of valve from the plain slide valve and automatic high-speed engines. There is one kind of automatic high-speed engine, however, which has valves similar to those of the Corliss engine.

Besides classifying steam engines according to their types of valves, they may also be classified in various other ways, among which are:

According to the position of the cylinder as

Horizontal engines
Vertical engines

According to the number of cylinders in which the steam is expanded as

Simple engines
Compound engines
Triple expansion engines
Quadruple expansion engines

According to the manner of handling the exhaust steam as

Condensing engines
Non-condensing engines

According to the use of the engine as

Stationary engines
Marine engines
Traction engines
Locomotive engines

A simple engine is one in which the steam is expanded in one cylinder only. In a compound engine the steam is first expanded

in one cylinder and the exhaust from this cylinder is led to a second cylinder where it is expanded further. In a triple expansion engine the total expansion of the steam is divided into three parts, each being performed in a separate cylinder, while in a quadruple expansion engine the total expansion of the steam is divided into four parts, each being performed in a separate cylinder. The general name of *multiple expansion* engines is used to designate any engine in which the expansion is performed in more than one cylinder. The reasons for dividing the expansion of the steam into parts will be considered in the next chapter.

A condensing engine is one in which the exhaust steam is cooled and condensed, thus reducing the back pressure against which the piston must make its return stroke. In a non-condensing engine the exhaust steam is turned into the atmosphere and the piston must make its return stroke against the pressure of the atmosphere plus enough pressure to force the exhaust steam through the exhaust pipe and ports. This pressure may amount to from 17 to 20 lb. per sq. in. absolute, or 2 to 5 lb. per sq. in. above atmospheric pressure.

85. Plain Slide-valve Engine.—The plain slide-valve engine is the simplest type. The engine, illustrated in Fig. 19 and de-

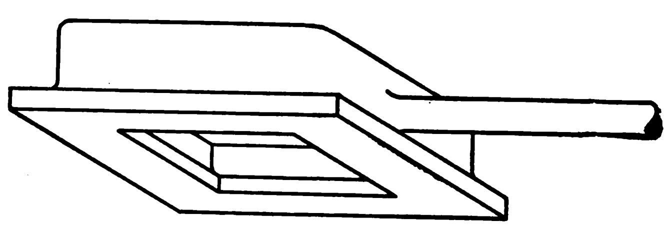

Fig. 62.

scribed in Chapter II, is an example of the plain slide-valve type of engine. This type of engine is named from the kind of valve used to distribute steam to the cylinder, which is called a plain slide valve. A plain slide valve is shown in Fig. 62. This valve consists of a rectangular hollow casting with one side open and the edges finished to fit closely on the valve seat, or side of the cylinder. In the type of valve shown here high-pressure steam surrounds the valve and the inside of the valve is filled with exhaust steam. The end edges of the valve control the admission and exhaust of steam and the sides prevent the steam from pass-

ing from one side of the valve to the other, or the live steam escaping into the exhaust pipe.

The slide valve is moved backward and forward by an eccentric, which is illustrated in Fig. 63. The eccentric consists of a circular disk fastened to the shaft but having its center a short distance

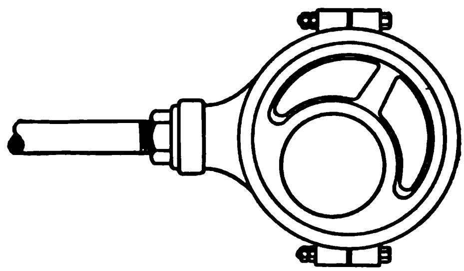

FIG. 63.

from the center of the shaft. The eccentric is surrounded by a strap in which the eccentric turns and the eccentric rod is connected to the strap. In turning, the eccentric gives the same motion to the eccentric rod that would be given by a short crank, that is, a backward and forward or reciprocating motion.

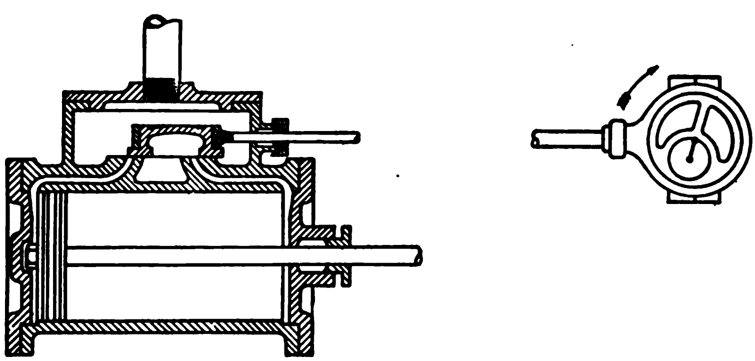

FIG. 64.

The action of the slide valve can best be explained by considering the series of operations which occur in one end of the cylinder, remembering that similar operations are occurring in the other end but at a different time. In Fig. 64 the piston is at the head end of the cylinder and just beginning its forward stroke, the shaft turning in the direction of the arrow.

In the position shown in Fig. 64 the valve is opening to admit

steam to the head end of the cylinder. The steam pressure moves the piston toward the right and the valve is opened wider, which allows steam to flow into the cylinder more freely. The valve soon reaches the end of its travel toward the right and begins to

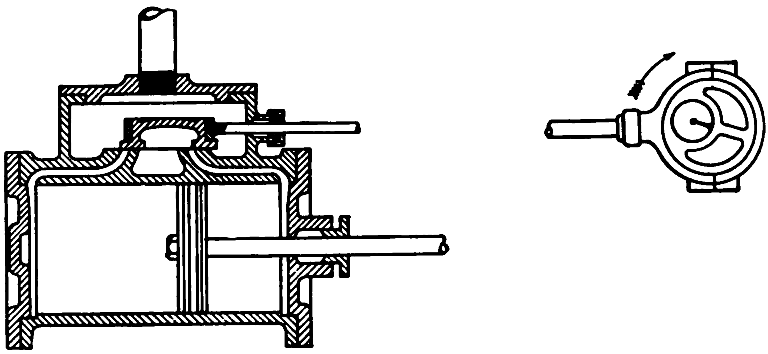

Fig. 65.

move toward the left, closing the head end steam port. Fig. 65 shows the valve just as it closes the head end steam port and it will be seen from this figure that the piston has not completed its forward stroke. Fig. 65 shows the positions of the valve and

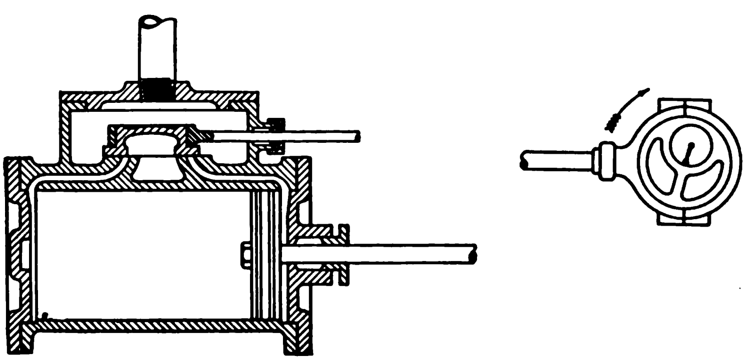

Fig. 66.

piston at cut-off. The valve continues to move toward the left, keeping the steam port closed and the steam expands behind the piston, pushing it toward the right. By the time the piston reaches the end of its forward stroke the inner edge of the valve begins to uncover the head end steam port, as shown in Fig. 66,

and gives the event called "release." This opens communication between the head end of the cylinder and the exhaust port; then if the steam still has any pressure above that of the atmosphere, this pressure immediately drops to the exhaust pressure.

At this point steam is admitted to the crank end of the cylinder and the piston is pushed to the left, which forces the spent steam in the head end of the cylinder into the exhaust pipe. This part of the stroke gives exhaust from the head end of the cylinder. The valve continues to move toward the left, opening the exhaust port wider and wider, until it reaches the end of its travel, when it begins to move toward the right and close the exhaust port. When the piston has reached the point in its return stroke shown

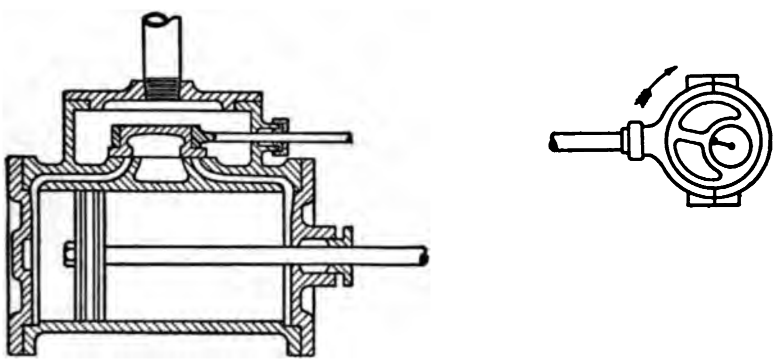

Fig. 67.

in Fig. 67, the valve has moved far enough to the right to close the exhaust port. From this point to the end of the return stroke the exhaust port remains closed and the piston compresses the steam which remains in the head end of the cylinder so that at the end of the stroke the clearance volume of the cylinder is filled with high-pressure steam. This completes the series of events in the head end of the cylinder.

By referring to Figs. 64, 65, 66 and 67 it will be seen that the valve is so constructed that at the same time admission and expansion are occurring in the head end of the cylinder, exhaust and compression are occurring in the crank end, and at the same time that exhaust and compression are occurring in the head end, admission and expansion are occurring in the crank end. Thus the events for both ends of the cylinder are performed in their

proper order and the engine is made to run continuously by means of a single slide valve and a single eccentric.

It will also be observed from the above figures that the angle between the eccentric and crank is a little greater than 90° and the engine runs in a direction to make the crank follow the eccentric. An engine may be made reversing, that is to run in either direction at will, by having two eccentrics on the shaft so arranged that the valve may be connected to and take its motion from either eccentric as desired. The crank and two eccentrics would then have the relative positions shown in Fig. 68 in which OC represents the crank and OE and OE' represent the eccentrics. When the valve takes its motion from the eccentric OE the engine runs in a clockwise direction and when its motion is taken from OE' the engine will run in a counter-clockwise direction.

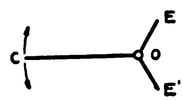

FIG. 68.

The most common form of reversing valve gear is illustrated diagrammatically in Fig. 69 and is known as the *Stephenson link motion.* In the Stephenson link motion the two eccentrics OE and OE' are connected by eccentric rods to a curved link. This

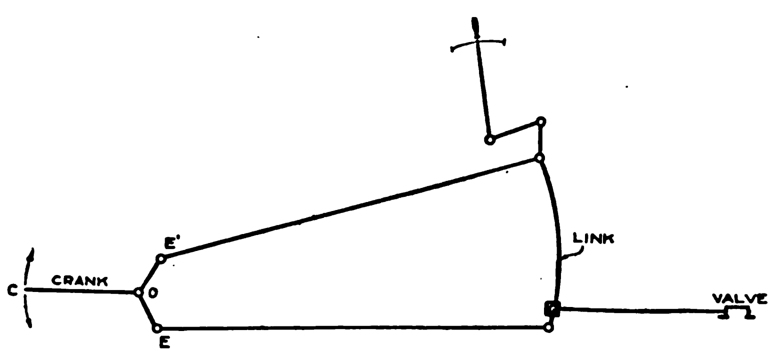

FIG. 69.

link has a slot which contains a block on the end of the valve rod. The link may be moved up or down, thus placing the valve rod in line with either eccentric rod. With the position of the link shown in Fig. 69 the valve rod is in line with the eccentric rod from OE and the valve takes its motion from this eccentric; therefore the engine will run in a clockwise direction. If the link is lowered the valve rod will be in line with the eccentric rod from OE' and the valve will take its motion from this eccentric,

which gives the engine a counter-clockwise direction of rotation. If the link is moved so that the valve rod is half-way between the two eccentric rods the motion of the valve will be slight because it is acted upon equally by both eccentrics, one giving a forward and the other a backward motion.

In the plain slide valve engine the point of cut-off is determined by the fixed position of the eccentric and, if the pressure of the steam supplied to the engine is constant, the amount of work performed in the cylinder will be constant. In order to prevent the speed of this type of engine from changing as the load on the engine changes, it is necessary to use some device for controlling the amount of work being performed in the cylinder. This is done by means of a governor so arranged that the pressure of the steam is reduced as the speed increases. Such a governor is called a *throttling governor*.

An engine whose speed is regulated by throttling or reducing the pressure of the steam supply uses a large amount of steam in proportion to the work it performs, or is inefficient, because the full pressure of the steam is used only when the load is greatest and for any smaller load a portion of the steam pressure is wasted. For this reason the slide valve engine is used only in small sizes when used on varying loads. A great many large marine engines are of the plain slide valve type but they work under practically constant loads and, when designed for these loads, are fairly economical.

The plain slide-valve engine is usually designed to run at slow or medium speeds, with a length of stroke somewhat greater than the diameter of the cylinder. They are simple in construction and cheap in cost, hence are much used where only a small amount of power is needed and where expert attendance is not obtainable. With ordinary care they last for a long time and do not easily get out of order. This type of engine uses from 35 to 60 pounds of steam per hour for each horse-power developed.

86. Automatic High-speed Engine.—The automatic high-speed engine is also a slide valve type of engine but it differs from the plain slide valve engine in having a balanced valve, in its method of controlling the speed, and in the general proportions of its parts. One form of automatic high-speed engine is shown in Fig. 70.

The balanced valve of the automatic high-speed engine, shown in Fig. 71, consists of a slide valve which has a smooth flat top

covered by a plate fastened to the cover of the steam chest. The valve slides between the valve seat and the balance plate, which fits against the valve tight enough to relieve it of the steam pres-

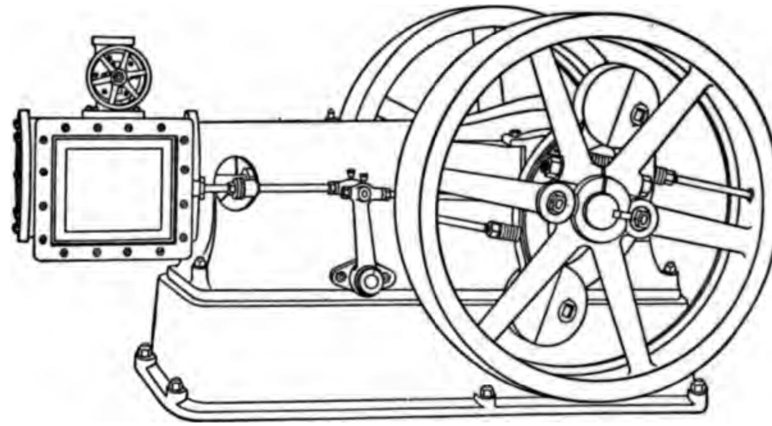

FIG. 70.

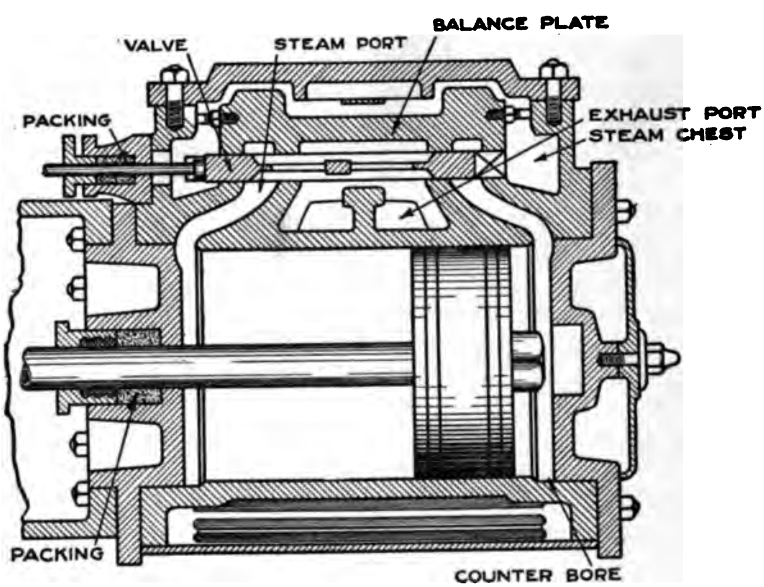

FIG. 71.

sure. If the full steam pressure is exerted against the back of a slide valve, the valve is pressed against the seat with an enormous

force, causing undue wear, requiring more power to move the valve, and preventing effective lubrication. The balance plate covers about 80 per cent. of the area of the valve, leaving 20 per cent. exposed to steam pressure. This is sufficient to keep the valve properly seated and yet is not enough to create undue friction.

Another common form of balanced slide valve is known as the piston valve, illustrated in Fig. 72. This type of valve is shaped like a spool, the large flat parts at the ends being the working faces of the valve. The valve moves in a direction parallel to its

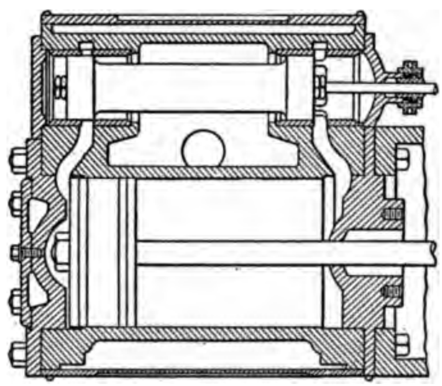

Fig. 72.

axis and slides over the ports in the same manner as an ordinary slide valve. Since steam pressure acts upon this valve in all directions it is perfectly balanced.

The speed of the automatic high-speed engine is regulated by controlling the volume of steam admitted to the cylinder at each stroke, instead of changing the steam pressure according to the load on the engine. This is a more efficient method of regulating the speed because the steam is admitted to the cylinder at full pressure all the time and none of the pressure is wasted. The volume of steam admitted to the cylinder is regulated by a governor located in the fly-wheel. The governor controls the point of cut-off by shifting the eccentric, to which it is attached, causing the cut-off to occur later in the stroke for a large load and earlier for a small load.

The automatic engine usually presents a short appearance, the parts being grouped closely together. As compared with the

plain slide valve engine, its cylinder and connecting rod are shorter in proportion to the diameter of the cylinder. They are made in these proportions because the desirable piston speed for all types of engines is about the same and in order to secure a large number of revolutions per minute and not exceed the desirable piston speed the stroke must be short as compared with the diameter of the piston.

The automatic high-speed engine is made for speeds up to about 350 revolutions per minute and in sizes up to about 600 horsepower. It has a close speed regulation at all loads and is therefore well adapted for direct connection to electric generators, a class of work which requires high and constant speed, and a large number of these engines are used in this class of service. These engines are also often connected to line shafting by means of belts and used for general power purposes. They are more efficient than the plain slide valve engine, using from 30 to 40 pounds of steam per horse-power per hour.

87. Corliss Engine.—The Corliss engine is an entirely different type from either of the two just described. Like the others it is named from its type of valve, which is known as the Corliss valve.

The Corliss valve is cylindrical and placed with its axis across the cylinder instead of parallel to it as with the piston valve.

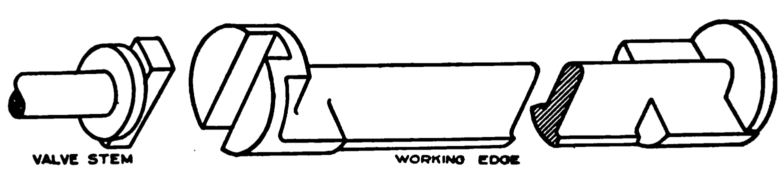

Fig. 73.

There are four of these valves to each cylinder, an admission valve for each end of the cylinder and an exhaust valve for each end. Each of these valves has an oscillating motion about its axis instead of sliding back and forth parallel to its axis, and it turns through an angle only large enough to uncover the port. The shape of the Corliss valve is illustrated in Fig. 73 which shows the valve removed from the cylinder.

Corliss valves obtain their motion from an eccentric which is fixed to the engine shaft, the motion being transmitted through an eccentric rod to the valves. The admission valves are connected

with the eccentric only at the times when they are being opened. When cut-off occurs the connection between them and the eccentric is released and they are closed quickly by the suction of a vacuum which is created at the time the valve is opened, by a piston in a dash pot. The valve then remains stationary until admission to that end of the cylinder again occurs. The exhaust valves are connected with the eccentric at all times but the connection is by means of links such that the valves move very slowly except when they are opening and closing.

The speed of the Corliss engine is governed by regulating the volume of steam admitted at each stroke to suit the load. This is done automatically by the governor which changes the point of cut-off by releasing the admission valve, allowing it to close earlier or later in the stroke as the speed increases or decreases.

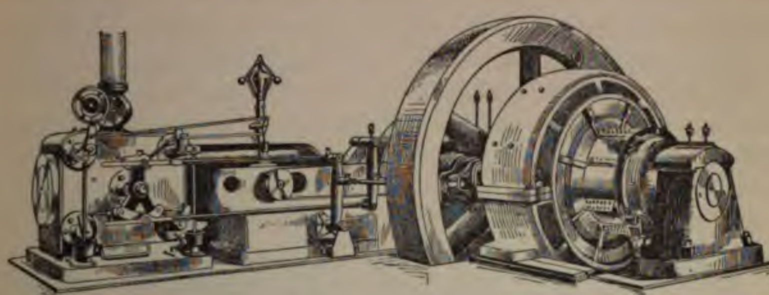

Fig. 74.

The construction of the Corliss valve gear is such that cut-off occurs very early in the stroke, which permits the steam to be expanded a large number of times, while, with a slide-valve engine, it is impractical to have cut-off occur earlier than about half stroke. Also with the slide valve, since one valve controls all of the events, an early cut-off gives an early compression, so that the extra work that might be gained from greater expansion of the steam is partly lost by the earlier compression. The admission and exhaust valves are separate in the Corliss engine; hence an early cut-off may be secured without an early compression.

A general view of a Corliss engine is shown in Fig. 74 which serves to give an idea of the proportions of its parts. It will be observed that this type of engine has a somewhat longer cylinder in proportion to its diameter and also a longer connecting rod than

other types of engines. This gives the whole engine an appearance of considerable length in proportion to its height.

The complicated valve mechanism used on Corliss engines makes it necessary to run them at relatively low speeds in order for the various parts to adjust themselves and work properly. In order to maintain a proper piston speed with a small number of revolutions per minute the length of stroke must be long. Corliss engines rarely run at higher speeds that 100 to 125 revolutions per minute and, in the larger sizes, the speed is lower than this.

The Corliss engine is the most efficient type of steam engine. It rarely uses over 25 pounds of steam per horse-power per hour and in the larger sizes its steam consumption is much less than this. This type of engine is made in sizes from 100 to 12,000 horse-power. The Corliss engine is particularly adapted to running mills and for other power purposes, on account of its smooth running qualities and its close speed regulation.

88. Four-valve Engine.—The four-valve engine is a type of medium and high-speed engine that has been developed in recent years. This engine, which is shown in Fig. 75, has the general

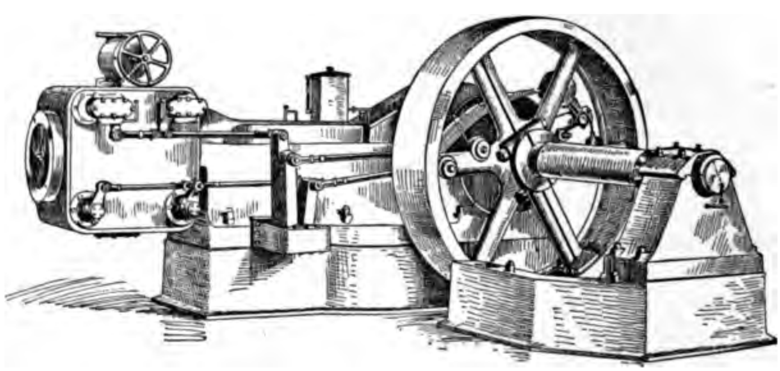

Fig. 75.

proportions of the automatic high-speed engine and has the same kind of speed regulating device, but has valves similar to those of the Corliss engine. As with the Corliss engine there is a valve for admission to each end of the cylinder and one for exhaust from each end, but all of these valves are connected to the eccentric at all times and are not disengaged as in the Corliss engine.

The four-valve engine combines many of the advantages of both the automatic high-speed and the Corliss types. The kind

of valve used permits a large port opening with a small movement of the valve and the clearance volume is reduced to a small amount. The shape of the valve is such that the total steam pressure acting upon it is small; hence the friction is small and efficient lubrication is easy. This type of engine is used on the same class of work as the automatic high-speed engine and it is made in the same sizes and speeds. Its steam consumption per horse-power per hour is slightly less than that of the automatic high-speed engine.

89. Steam-engine Efficiencies.—In engineering work the term efficiency is usually understood to mean the ratio of the work or energy gotten from a machine or process to the work or energy supplied, or, expressed as a formula,

$$\text{Efficiency} = \frac{\text{work obtained}}{\text{work supplied}}$$

This ratio will always be less than one, or 100 per cent. for a steam or other engine, because no machine can deliver as much work as is put into it, on account of friction and other losses.

In the above formula for efficiency, both the work obtained and the work supplied must be expressed in the same units, either in foot-pounds or in British thermal units. Since it is more convenient to measure the indicated horse-power of an engine than the brake horse-power it is customary to base the work obtained upon the indicated horse-power. The "work obtained" may be taken as one horse-power acting for one hour which if, expressed in heat units will be 2545 B.T.U. The "work supplied" by the engine must then be expressed as the number of heat units contained in the steam supplied to the engine per horse-power per hour. The amount of heat in the steam supplied is calculated above the temperature of the exhaust rather than above 32° F. (the temperature from which quantities given in the steam table are calculated), because no engine could use all of the heat in steam down to a temperature of 32° F; hence, if the heat supplied is based on this temperature, the engine will be charged up with some heat which it is not capable of turning into work.

The above formula for efficiency, when applied to a steam engine then becomes

$$\text{Efficiency} = \frac{2545}{H_1}$$

in which H_1 is the number of B.T.U. supplied to the engine per hour for each horse-power, calculated above exhaust temperature.

Example:

What is the efficiency of an engine which develops 125 I.H.P. and uses 22 pounds of steam per I.H.P. per hour, the admission pressure being 130 lb. per sq. in. absolute and the exhaust pressure being 18 lb. per sq. in. absolute? The quality of the steam supplied to the engine is 97%.

Solution:

B.T.U. in one pound of steam, above 32° F.

$$=(h+qL)=(318.6+.97\times 872.3)$$
$$=(318.6+846)=1164.6$$

Number B.T.U. between 32° and exhaust temperature

$$=222.4-32=190.4$$

B.T.U. in one pound of steam above exhaust temperature

$$=1164.6-190.4=974.2$$

B.T.U. in 22 pounds of steam, above exhaust temperature

$$=22\times 974.2=21432.4$$

$$\text{Efficiency}=\frac{2545}{21432.4}=.118 \text{ or } 11.8\%$$

The above method of expressing efficiency is useful in giving an idea of the proportion of the heat supplied to the engine which is turned into work and also to compare the efficiency of one steam engine with that of another which is operating under the same conditions. It is often desirable, however, to compare the performance of one kind of engine with that of another, as for example, to compare the performance of a gas engine with the performance of a steam engine. This cannot be done by calculating the efficiency of both engines and then comparing their efficiencies, because these efficiencies are calculated from different considerations and such a comparison would not give an idea of the relative performances of the two engines. In order to make such a comparison as this it is necessary to have some standard of efficiency by which each engine may be compared.

90. The Carnot Cycle.—A convenient way of comparing engines of different kinds is to calculate the efficiency they would have if they were working on a perfect cycle, in which case they would turn into work the largest possible proportion of the heat supplied to them. In the perfect cycle all of the heat taken into the engine is at the maximum temperature and all of the heat rejected from the engine is at the minimum temperature, so that all of the heat utilized is changed into work by falling through the greatest possible range of temperature, thus enabling it to perform the greatest possible amount of work. Such a cycle

is called Carnot's cycle, from the name of the man who devised it. Carnot's cycle is not a practical one and engines do not operate upon it, but the efficiency of this cycle is useful as a standard of comparison because it gives the maximum efficiency for a given gas working between given limits of temperature.

In Carnot's cycle the gas is first expanded isothermally, that is, at constant temperature; it is then expanded adiabatically, that is, with no heat entering or leaving the cylinder; this is followed by an isothermal compression, and then by an adiabatic compression. All of the heat supplied to the engine is taken in during the isothermal expansion at the maximum temperature and all of the heat rejected by the engine is rejected during the isothermal compression at the lowest temperature. There is no transfer of heat at any other part of the cycle; hence, all of the heat energy that remains in the cylinder performs work by falling through the entire range of temperature, a condition which porduces maximum efficiency.

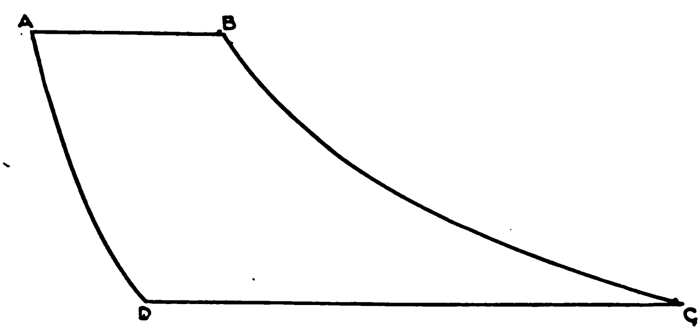

FIG. 76.

If the Carnot cycle were applied to a steam engine the work diagram from the cylinder would be similar to that shown in Fig. 76. In this diagram the admission line *AB* is an isothermal expansion since the volume of steam in the cylinder is increasing and its temperature remains constant, which are the only conditions necessary for an isothermal expansion. During this process heat is being taken into the cylinder. The next stage in the cycle is the adiabatic expansion, represented by the line *BC*. Isothermal compression, or contraction, is represented by the exhaust line *CD*, the volume of steam in the cylinder decreasing and its temperature remaining constant. During this process

heat is rejected from the cylinder. The final stage of the cycle is the adiabatic compression, represented by the line DA.

It is in the last step of the cycle described above that the cycle of the actual steam engine differs most from the true Carnot cycle because in the cycle of the steam engine the compression is not usually carried up to admission and because only a part of the steam is compressed at all, the larger part leaving the cylinder and dropping out of the cycle altogether. In the true Carnot cycle all of the working substance is supposed to complete the entire cycle.

The amount of heat taken in during an isothermal process is equal to KT_1 in which K is a factor depending upon the weight and kind of gas and T_1 is its absolute temperature, and the heat rejected during an isothermal compression is equal to KT_2, in which T_2 is the absolute temperature of the gas during compression. The amount of heat energy turned into work in the cylinder is the difference between the amount of heat taken in and the amount rejected, or

$$\text{Work performed} = KT_1 - KT_2$$

Hence the efficiency of this cycle is

$$\text{Efficiency} = \frac{KT_1 - KT_2}{KT_1}$$

By cancelling the quantity K which appears in both the numerator and denominator the above formula becomes

$$\text{Efficiency} = \frac{T_1 - T_2}{T_1}$$

In which

T_1 is the maximum absolute temperature in the cylinder
T_2 is the minimum absolute temperature in the cylinder

Example:

Calculate the ideal or theoretical efficiency of the engine mentioned in the preceding example if the engine was operating on the Carnot's cycle.

Solution:

Maximum temperature of the steam taken into the engine
$= 347.4°$ F. or $347.4 + 460 = 807.4°$ absolute.

Minimum temperature of steam rejected from the engine
$= 222.4°$ F. or $682.4°$ absolute.

$$\text{Efficiency} = \frac{807.4 - 682.4}{807.4} = \frac{125}{807.4} = .1547 \text{ or } 15.47\%$$

Example:

Compare the ideal efficiencies of the steam engine in the above example with that of a gas engine which develops a temperature of 3000° F. in the cylinder and exhausts the burnt gases at a temperature of 1200° F.

Solution:

Maximum absolute temperature developed in gas engine
$=3000+460=3460°$

Absolute temperature of gases rejected from engine
$=1200+460=1660°$

$$\text{Efficiency}=\frac{3460-1660}{3460}=\frac{1800}{3460}=.52 \text{ or } 52\%.$$

While a statement of either the actual efficiency of a steam engine or its efficiency based on Carnot's cycle indicates its performance, it is customary also to state the performance of a steam engine in terms of the number of pounds of dry steam used by it per I.H.P. per hour. In all cases the actual number of pounds of steam used, if wet, may be reduced to pounds of dry steam used by dividing the total number of heat units in the wet steam by the total heat of one pound of dry steam of the same pressure. For several important classes of engines, good average performance, with saturated steam is about as follows:

Small non-condensing engines	30 lb.
Large non-condensing engines	25 lb.
Locomotives	24 lb.
The medium range of condensing engines	17 lb.
Large and well-kept power engines	13 lb.
The best pumping engines	11 lb.

91. Condensers.—From the above discussion of efficiencies it may be seen that if the difference in temperature between admission and exhaust is increased the efficiency will also be increased. This difference may be increased in two ways, first, by increasing the pressure of the steam admitted to the engine, and second, by decreasing the pressure of the exhaust steam.

The effect on the indicator diagram of increasing the admission pressure is shown in Fig. 77 in which the shaded area represents the additional work obtained by adding 10 lb. per sq. in. to the admission pressure. If the original admission pressure is 120 lb. per sq. in. absolute and this is increased 10 lb. per sq. in. the temperature of admission will be increased from 341.3° F. to 347.4° F. or only 6.1°.

The effect on the indicator diagram of condensing the exhaust steam and thereby causing the engine to exhaust into a partial

vacuum, is shown in Fig. 78. In this case the back or exhaust pressure has been reduced 10 lb. per sq. in., the same as the increase in the preceding example, but in this case the additional work obtained from the engine is considerably greater since the reduction in pressure is effective for almost a complete stroke

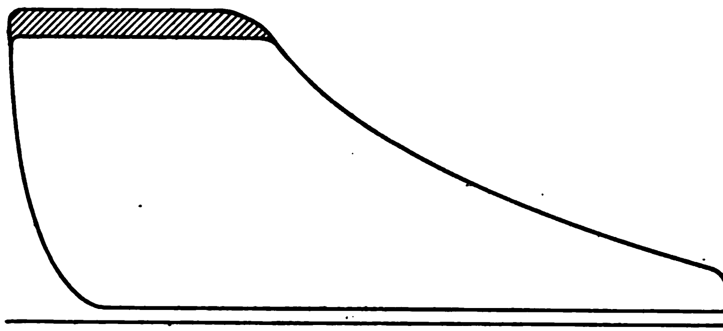

Fig. 77.

while the increase in admission pressure is effective for a comparatively small part of the stroke. If the original exhaust pressure is 16 lbs. per sq. in. absolute the exhaust temperature is decreased from 216.3° F. to 170.06° F. or 46.24°. This shows that a greater difference between admission and exhaust temperatures is produced by lowering the exhaust pressure than by increasing the

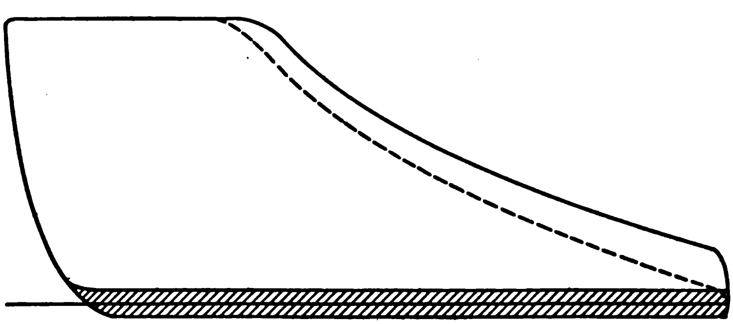

Fig. 78.

admission pressure the same number of pounds and hence increases the efficiency more, since the efficiency depends upon this difference in temperature. If the exhaust pressure were lowered, as shown in Fig. 78, the steam would be cut off earlier during admission, as indicated by the dotted line, in order to

prevent the pressure at the end of expansion from being too high. The amount by which the admission line is shortened when the exhaust pressure is decreased is an approximate measure of the effect produced by the use of a condenser. The length of the admission line shows that the volume of steam admitted to the cylinder is much smaller when the condenser is used than when it is not used; hence, the amount of steam used to produce the same amount of work is less with a condenser than without.

QUESTIONS

108. A certain automatic high-speed engine has a cylinder 20 in. in diameter and a stroke of 21 in. A Corliss engine has a cylinder 20 in. in diametes and a stroke of 42 in. Explain why there is such a great difference in the strokes of these two engines.

109. What is the best method of speed regulation? Give the reasonr for your answer.

110. What is the object in using a condenser? What becomes of the heat taken out of the steam by a condenser?

111. The power of a steam engine may be increased by the use of a condenser or by increasing the initial steam pressure. Which of these methods is preferable? Give the reasons for your answer.

112. Explain why any engine operating on Carnot's cycle gives the highest possible efficiency.

113. A steam engine plant consumes 2¼ pounds of coal for each I.H.P. developed by the engines. The coal burned has the following analysis: Carbon 74%; hydrogen 5%; oxygen 4%. What is the efficiency of this plant?

114. An engine develops 350 I.H.P. and uses 17 lbs. of steam per I. H.P. The steam used has a pressure of 130 lb. per sq. in. gage pressure and a quality of 97.5%. The exhaust from the engine passes into a condenser whose gage registers 22 in. vacuum. What is the efficiency of the engine?

115. State the steam consumption of the above engine in terms of pounds of dry steam used per hour.

116. What is the efficiency of the above engine based on Carnot's cycle?

CHAPTER XII

MULTIPLE EXPANSION ENGINES

92. Action of Steam in the Cylinder.—The low efficiency of the steam engine shows that a large part of the heat energy supplied to it is not turned into work, but is lost or wasted. Even the best engines utilize only about 20% of the heat supplied to them, leaving about 80% to be accounted for by the various losses incident to the operation of the engine. Radiation of heat from the engine and the friction of its moving parts account for only a small part of the loss. A much larger part is accounted for by the heat contained in the exhaust steam. As shown in the preceding chapter, this loss may be reduced considerably by the use of a condenser, which lowers the exhaust pressure and makes a larger proportion of the total supply of heat available for useful work, but, even with the use of a condenser, the loss of heat in the exhaust is considerable.

For a long time after the steam engine was invented, the three sources of loss mentioned above were thought to be the only ones. It was discovered later, however, that a very serious loss was occurring in the cylinder due to the interchange of heat between the steam and the cylinder walls. In order to understand this loss of heat the action of the steam in the cylinder must be studied, and for this purpose it is convenient to consider the events occurring in only one end of the cylinder.

The inside of the cylinder of an engine is subject to great changes in temperature, greater, in fact, than occur between the hottest day of summer and the coldest day of winter. For example, if the steam is admitted at 150 lb. per sq. in. pressure (temperature 358.5° F.) and is exhausted at a pressure of 4 lb. per sq. in. (temperature 153.0° F.), the inside of the cylinder is subject to a change of temperature during each stroke amounting to 205.5°. During exhaust the inside of the cylinder is in contact with steam at a low temperature, hence it becomes cooled. Compression raises the pressure and temperature of a part of the steam, but this affects only a small area near the ends of the cylinder

walls, hence the net effect of exhaust and compression, as far as temperature is concerned, is to leave the cylinder walls at a much lower temperature than that of the admission steam. When admission occurs, the incoming steam at high temperature meets the comparatively cold cylinder walls and a considerable part of it is condensed. As the piston moves forward on the admission stroke more and more of the cold cylinder walls are uncovered and more of the admission steam is condensed so that by the time cut-off occurs from 30 to 60 per cent. of the steam which has entered the cylinder has been condensed. The steam condensed by the cold cylinder walls forms a thin film of water on the inside of the cylinder and this water is at the boiling temperature corresponding to the admission pressure.

After cut-off occurs, the piston continues to expose more of the cold cylinder walls, and condensation from this cause continues; but at the same time the steam is expanding and its temperature is falling with the decreasing pressure. The decreasing temperature, because of the smaller difference in temperature between the walls and the steam, tends to check condensation due to contact with the cylinder walls. At the same time, as soon as the temperature of the steam falls below that of the water deposited on the cylinder walls by condensation, the film of water begins to re-evaporate. A point is reached soon after cut-off when the re-evaporation balances the condensation, and from this point to the end of the stroke the steam becomes dryer.

As expansion progresses re-evaporation continues at a faster and faster rate, due to the greater difference in temperature between the steam and the film of water on the cylinder walls. Unless condensation has been excessive in the earlier parts of the stroke, all of the film of water may be re-evaporated by the time the piston has reached the end of its stroke.

It might be thought that the steam formed during expansion from the re-evaporation of moisture could do work by expanding behind the piston, and such is, in fact, the case, but it should be remembered that most of this steam is formed at a comparatively low pressure and hence has but little ability to do work.

The moisture on the cylinder walls, in evaporating, absorbs the latent heat of evaporation for the pressure at which evaporation occurs, and this amount of heat is absorbed from the cylinder walls, which cools them. A small weight of moisture evaporated in the cylinder will produce a large cooling effect, because the

latent heat of evaporation is involved, and this is large compared with the weight of moisture evaporated.

The changes of temperature within the cylinder occur in rapid succession, and these changes do not have time to penetrate very far into the metal. The outside surface of the cylinder walls assumes a constant temperature when the engine is running, while the inside surface is subject to great fluctuations of temperature; hence the give and take of heat affects a comparatively small amount of metal. While the difference between the amounts of heat absorbed from and given to the cylinder walls is small, the cooling effect is large because of the small amount of metal affected and its low specific heat.

The cooling effect of re-evaporation is increased by any moisture that may be brought into the cylinder by the admission steam, because this adds to the water that may be evaporated and, since it has not been condensed in the cylinder, it has given no heat to the cylinder walls.

If there is very much water in the cylinder at the point of cut-off, all of it may not be re-evaporated at the end of expansion, but as soon as the sudden drop in pressure occurs at release, re-evaporation progresses very rapidly, so that during exhaust the steam in the cylinder may be perfectly dry.

From the above discussion it will be evident that the evil effects of cylinder condensation and re-evaporation will be increased by anything which increases the condensation or the range of temperature in the cylinder. The use of a condenser for decreasing the exhaust pressure increases the range of temperature in the cylinder and therefore increases re-evaporation. An early cut-off increases the number of expansions of the steam or the range of pressure and, for this reason, also increases re-evaporation. A late cut-off increases condensation during admission by increasing the amount of surface exposed to high temperature steam. Increasing the admission pressure increases the range of temperature in the cylinder and therefore increases re-evaporation.

The means most commonly used for reducing the harmful effects of cylinder condensation and re-evaporation are: first, providing a supply of superheated steam for the engine; and second, dividing the total expansion of the steam into two or more parts and performing each in a separate cylinder, in order to reduce the range of temperature in any one cylinder. Supplying

an engine with superheated steam is effective in reducing cylinder condensation by furnishing a store of heat which may be given up to the cylinder walls without producing condensation. Superheated steam contains an amount of heat over and above that required to saturate it, and this amount of heat may be given up to the cylinder walls and still leave the steam in a saturated condition. Nearly all of the condensation in the cylinder occurs before cut-off; hence, if the steam contains enough superheat so that the steam in the cylinder at cut-off will be dry saturated steam, nearly all of the condensation will be prevented. Usually from 100° to 200° of superheat is sufficient for this purpose. Since cylinder condensation is greatest in the smaller and more uneconomical classes of engines, these are the ones which derive the most benefit from superheated steam.

93. Compounding.—By compounding is meant dividing the total expansion of the steam into a number of parts and performing each one in a separate cylinder. When the total range of pressure is divided between several cylinders, the total range of temperature is also divided, and each cylinder will then be subject to smaller differences of temperature than if all of the expansion occurred in one cylinder. This decreases the condensation and the cooling effects of re-evaporation, because these things depend upon the range of temperature to which the cylinder is subjected.

The number of parts into which the total expansion is divided depends upon the pressure of the steam supplied to the engine and upon the use of the engine. In marine work, where compounding is more generally practised than in stationary work, the number of parts into which the total expansion is divided for different boiler or admission pressures is about as follows:

Simple engines..........	30 to 70 lb. per sq. in. gage
Compound.............	80 to 120 lb. per sq. in. gage
Triple expansion........	140 to 180 lb. per sq. in. gage
Quadruple expansion....	200 to 250 lb. per sq. in. gage

With stationary engines there is a tendency to divide the total expansion of the steam into a fewer number of parts and to use higher pressures. Compound condensing engines are often run with pressures of 120 to 150 lb. per sq. in. gage, while the compound locomotive, which is never used with a condenser, is sometimes supplied with steam having a pressure of 200 to 225 lb. per sq. in. gage.

An ideal expansion line for steam expanding from 120 lb. to 1.6 lb. is shown in Fig. 79, the diagram *ABCDEFG* representing an indicator diagram from an engine having no clearance. The line *AB* represents the admission line, which is very short as compared with the length of the line *GF*, which represents the volume of the low-pressure steam after expansion and therefore also represents the volume of the cylinder. The short admission line is necessary if the steam is to be expanded in one cylinder through the full range of pressure. It will be observed that if the entire expansion occurred in a single cylinder, this cylinder would have to be large enough to accommodate the volume of steam

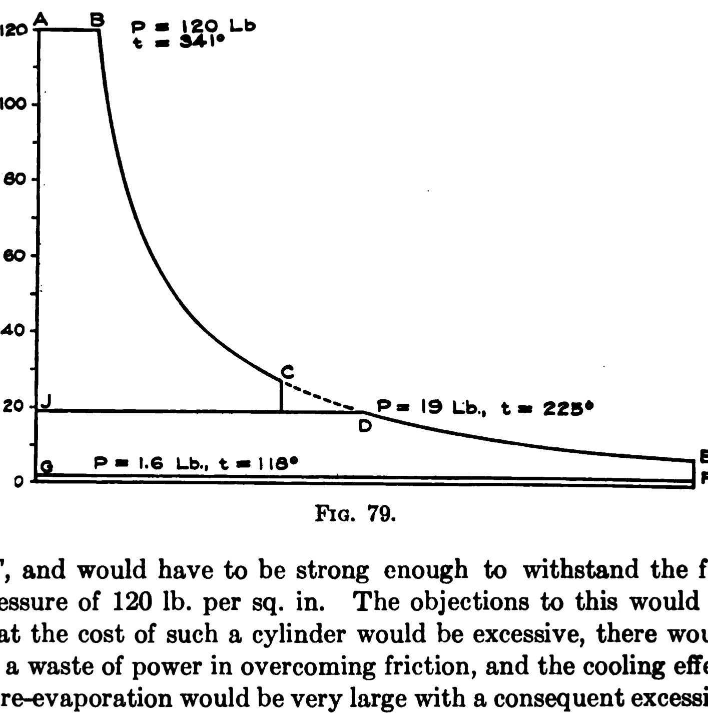

FIG. 79.

GF, and would have to be strong enough to withstand the full pressure of 120 lb. per sq. in. The objections to this would be that the cost of such a cylinder would be excessive, there would be a waste of power in overcoming friction, and the cooling effect of re-evaporation would be very large with a consequent excessive condensation.

Now, suppose that a line *JD* is drawn across the diagram at such a height that the diagram will be divided into two equal parts. If the two parts into which the expansion of the steam is divided are performed in separate cylinders, the first one will have a volume *JC* and would be built to withstand the full steam pressure of 120 lb. per sq. in. This cylinder would admit a vol-

ume of steam AB and would expand it to the volume JC. The expansion would not be carried further than the point C, because it is desirable to have enough pressure in the cylinder at release to force the steam out of the cylinder rapidly, and also because the extra amount of work obtained by complete expansion would not be enough to balance the loss of work in friction while the piston was moving through this part of the stroke. The exhaust from the first cylinder would form the supply for the second. This cylinder would have a volume equal to GF, the same as would a cylinder designed for the entire expansion, but, as the supply of steam for the second cylinder has a pressure of only 20 lb., it would not have to be as strong as a single cylinder, hence would be cheaper to construct.

The second cylinder would admit the volume of steam JD at a pressure of 19 lb. and would expand it to the volume GF, when its pressure would be 1.6 lb. If the total expansion occurred in a single cylinder this cylinder would be subjected to the full range of temperature, 225°, and since its wall surface would be large, condensation would be excessive. By dividing the expansion into two parts, each cylinder experiences a range of temperature of only about 112°; that is, the range in temperature has been cut in half and the cylinder surface has not been doubled, hence the condensation and re-evaporation in the two cylinders would be less than in a single cylinder subject to the full range of temperature. This decreases materially the large loss of heat that would otherwise occur through condensation and re-evaporation; but, on the other hand, the engine would be more complicated and therefore more expensive, and the friction loss would be increased by the greater number of moving parts.

94. Compound Engines.—Compound engines are divided into two classes, based upon the arrangement of cylinders. These are called *tandem-compound*, in which one cylinder is placed behind the other, and *cross-compound*, in which the cylinders are placed parallel with each other.

The tandem engine, as illustrated in Fig. 80, has only one piston rod, connecting rod, and crank. The piston rod extends from one cylinder through the other and has both pistons attached to it. The exhaust pipe from the high-pressure cylinder passes directly to the low-pressure cylinder, and as this pipe is short it has but little storage capacity. The tandem-compound engine

is simple in construction, but the parts must be made large in order to carry the heavy stresses.

The cross-compound engine, illustrated in Fig. 81, has two pistons, piston rods, connecting rods, and cranks, hence it is similar to two simple engines placed parallel with each other and con-

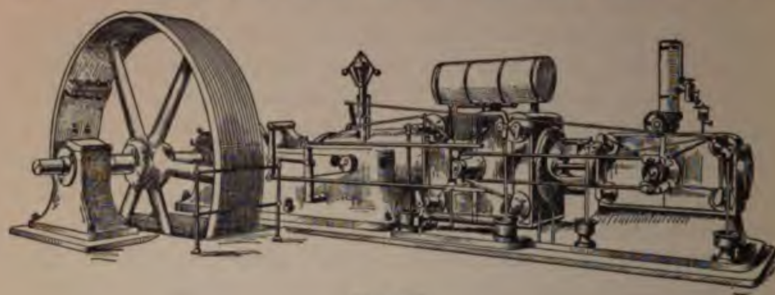

Fig. 80.

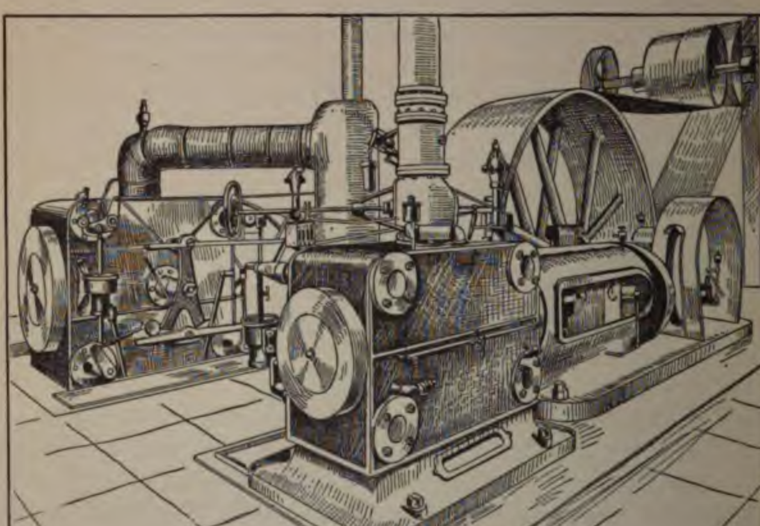

Fig. 81.

nected to the same shaft. The cranks are usually placed 90° apart, which gives a more uniform turning effort on the shaft. Since each side of the engine transmits only half of the power, the parts of the engine are made smaller, but the larger number of parts makes this type of engine more expensive than the tandem-

compound. The exhaust pipe from the high-pressure cylinder extends across to the low-pressure cylinder and contains a receiver or vessel in which steam may be stored. This is made necessary by the cranks being placed 90° apart, as explained in a later paragraph.

The action of the steam in the two classes of engines mentioned above is quite different. In the tandem engine the pistons have the same length of stroke, and move in unison with each other, beginning a stroke at the same time and ending it at the same time. For this reason the steam exhausted from the high-pressure cylinder may be passed directly into the low-pressure cylinder without the intervention of any valves on the latter cylinder and without any storage space or receiver between the cylinders. In this case the valves and governor on the high-pressure cylinder control the action of the steam and the amount of work performed in both cylinders.

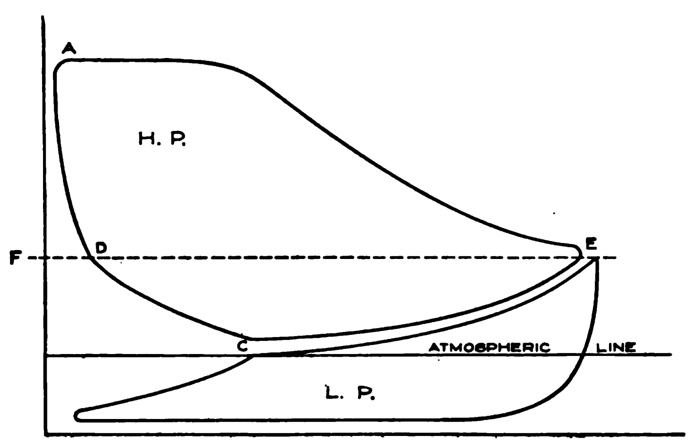

FIG. 82.

95. Cross-compound Engines.—The action of the steam in both cylinders of a cross-compound engine with cranks set 180° apart and without valves on the low-pressure cylinder, may be studied best by considering the indicator diagrams shown in Fig. 82. This illustration shows the diagram from the high-pressure cylinder, marked HP, and that from the low pressure, marked LP, placed in their correct relative positions, that is, so that the return stroke for the high-pressure cylinder is the admission stroke for the low-pressure cylinder. These diagrams do not, however,

show correctly the division of work between the cylinders, because, being drawn to the same scale of pressure and stroke, they do not take into account the different diameters of the cylinders.

After the supply of steam is cut off from the high-pressure cylinder, the steam expands in this cylinder until released. During exhaust from the high-pressure cylinder, the steam flows directly into the low-pressure cylinder. Since the diameter of the low-pressure cylinder is larger than that of the high-pressure cylinder and both pistons move at the same speed, the volume displaced in the low-pressure cylinder is greater than that displaced in the high-pressure cylinder. The result of this is that each cubic foot of exhaust steam pushed out of the high-pressure cylinder flows into a larger volume than one cubic foot in the low-pressure cylinder, and its pressure therefore falls. This is why the exhaust from the high-pressure cylinder and the admission to the low-pressure cylinder show a continually falling pressure. When the point of compression in the high-pressure cylinder is reached, the supply of steam for the low-pressure cylinder is stopped and the steam then in the low-pressure cylinder expands with a rapidly falling pressure, since no new steam is being supplied.

It will be observed from Fig. 82 that the range in temperature in the high-pressure cylinder is that represented by the change in pressure from A to C, which is greater than it would have been if there were less drop in pressure during exhaust. Also the range in temperature in the low-pressure cylinder is that due to the difference in pressure between E and exhaust pressure from the low-pressure cylinder. Since the pressure at E is greater than that at C, the range in temperature is greater in both cylinders than would be indicated by a division of the work into two equal parts.

The above analysis of the action of steam in the cylinder of a cross-compound engine applies only to those engines which have no valves on the low-pressure cylinder or to those engines which have only one valve for both cylinders and this valve so arranged that cut-off in the low-pressure cylinder occurs at the same time as compression in the high-pressure cylinder. This type of engine is not used to a large extent and is made only in comparatively small sizes. A more common arrangement either in tandem-compound engines or in cross-compound engines with cranks

placed 90° apart is to have separate valves on each cylinder which may be adjusted independently of each other. Engines of this kind must necessarily be supplied with a receiver or storage space in which the exhaust steam from the high-pressure cylinder may be stored if cut-off in the low-pressure cylinder does not occur at the same time as compression in the high-pressure cylinder. If the cylinders are placed near each other so that the connecting passages are short, the receiver is usually in the form of a separate vessel connected in the passage between the two cylinders; but when the cylinders are some distance apart, the passage connecting the two cylinders has enough volume to act as a receiver, and no separate vessel is necessary.

96. Tandem-compound Engines.—The presence of a receiver modifies somewhat the action of the steam in the cylinders from

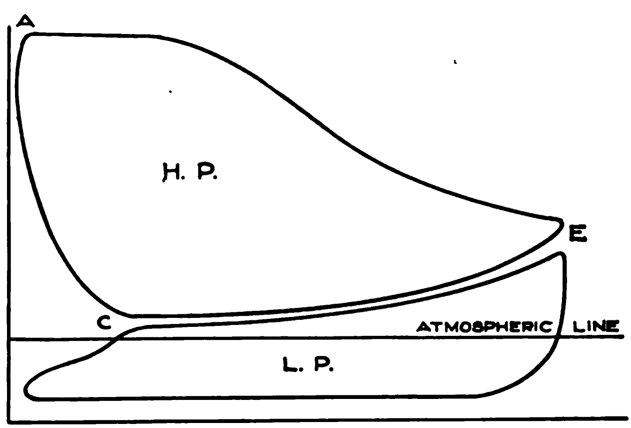

FIG. 83.

that described above and illustrated in Fig. 82. For a tandem-compound engine in which the connecting passage acts as a receiver, or for a cross-compound with cranks 180° apart and supplied with a receiver, the action of steam in the cylinders may be shown by the diagrams in Fig. 83, which are similar to those shown in Fig. 82 except that cut-off in the low-pressure cylinder does not occur at the same time that compression occurs in the high-pressure cylinder.

In this case, it will be observed from Fig. 83 that cut-off in the low-pressure cylinder occurs a little after half stroke and considerably before compression occurs in the high-pressure cylinder.

When cut-off occurs in the low-pressure cylinder, the steam then in that cylinder expands in the usual manner. The high-pressure cylinder, however, has not finished exhausting at this time; hence the exhaust from the high-pressure cylinder is stored in the receiver. Since no steam is being drawn from the receiver at this time, the pressure in it, which is also the exhaust pressure of the high-pressure cylinder, increases as shown by the line CD in Fig. 83. At D compression occurs in the high-pressure cylinder and the exhaust valve closes communication with the receiver.

The point of cut-off in the low-pressure cylinder controls the increase of pressure in the receiver, from C to D, the increase of pressure being greater with an early cut-off and smaller with a later cut-off. The cut-off in the low-pressure cylinder must be so timed that the pressure in the receiver will be the same at D as at E, the point where the exhaust valve on the high-pressure cylinder opens. If the pressure at D is not as high as at E, the pressure at the end of expansion in the high-pressure cylinder will be greater than that in the receiver and there will be a drop of pressure the next time the exhaust valve on the high-pressure cylinder opens. This would produce a waste of pressure and a loss of work, which is to be avoided if possible.

97. Cross-compound with Receiver.—The action of steam in the cylinders of a cross-compound engine with cranks set 90° apart presents another interesting case. An engine of this kind must necessarily be supplied with a receiver because one piston is at mid-stroke when the other is at the end of its stroke; hence exhaust from the high-pressure cylinder progresses for one-half of a stroke when no steam is being admitted to the low-pressure cylinder, and it is necessary to have a receiver in which to store this steam.

The diagrams from the high- and low-pressure cylinders of an engine of this type are shown in Fig. 84. These diagrams are not drawn in the usual manner, but instead the low pressure diagram is displaced one-half stroke from the high pressure diagram in order to show the relative pressures in the cylinder at any instant.

It will be observed from Fig. 84 that the exhaust pressure in the high-pressure cylinder increases gradually from the beginning to the middle of the exhaust stroke. The reason for this is that during this part of the stroke the high-pressure cylinder is exhausting into the receiver and the low-pressure cylinder is not taking any steam from it; hence the exhaust pressure in the high-

pressure cylinder, which is also the receiver pressure, increases. When the high-pressure piston reaches mid-stroke the low-pressure cylinder begins to admit steam, since the cranks are 90° apart, and the receiver pressure is reduced. Thus, the high-pressure exhaust line rises from beginning to mid-stroke and falls from mid-stroke to the point of compression.

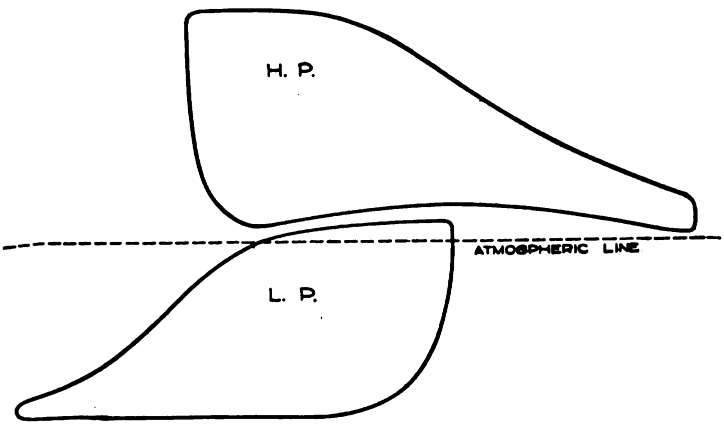

Fig. 84.

The admission line for the low-pressure cylinder follows the shape of the last half of the exhaust line of the high-pressure cylinder; hence it shows a decreasing pressure. In the low-pressure diagram shown in Fig. 84, cut-off occurs at or before

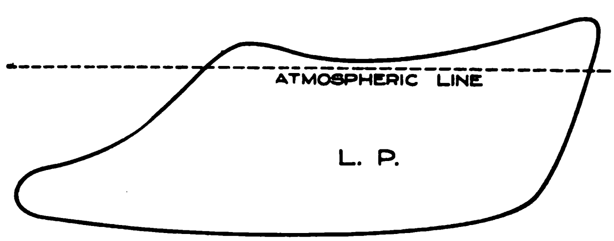

Fig. 85.

mid-stroke, or before the high-pressure piston has completed its stroke. If cut-off in the low-pressure cylinder occurs *after* half stroke the high-pressure piston will have started on its return stroke and exhaust will have commenced from the other end of the cylinder; hence the pressure in the receiver will again begin

to increase and this will produce a corresponding increase in the admission pressure for the low-pressure cylinder. The effect of the second admission of steam into the receiver before low-pressure cut-off is illustrated in Fig. 85, where the admission pressure for the low-pressure cylinder is shown decreasing up to mid-stroke and to increase from mid-stroke to the point of cut-off. This second increase in pressure is called "second admission," and it is found only when cut-off in the low-pressure cylinder occurs after mid-stroke.

One of the advantages of a cross-compound engine with cranks 90° apart is illustrated by Fig. 84, which shows that the range of temperature in it is less than in the cylinders of a cross-compound with cranks set 180° apart (Fig. 82), or a tandem-compound (Fig. 83), because the exhaust from the high-pressure cylinder shows a more uniform pressure. The variations in pressure illustrated in Figs. 82, 83, 84, and 85 will not show to such a marked degree on the actual indicator diagrams because the high pressure diagram is drawn with a stiff indicator spring. The variations in pressure in the low-pressure admission may be detected easily on the actual diagram, however, because this diagram is drawn with a weak spring.

98. Advantage and Disadvantage of Compounding.—The principal advantage derived from compounding is the reduction of cylinder condensation and re-evaporation. The way in which compounding accomplishes this object has already been treated quite fully. A secondary advantage is that compounding permits the economical use of higher steam pressures and a greater number of expansions of the steam than can be used economically in the simple engine. By making the cut-off sufficiently early steam may be expanded as many times in a single cylinder as in two or more cylinders, but a large number of expansions in a single cylinder is accompanied by a large loss from cylinder condensation, hence this would not be economical. Neither would the use of high pressures be economical unless the steam may be expanded a large number of times; hence high steam pressures and a large number of expansions may be used economically only in compound engines.

Most of the disadvantages of compounding arise from the greater complication of these engines which makes them more expensive in first cost and in cost of repairs. The greater number of parts also causes a larger loss of power through friction than in

non-compound engines. In these respects triple expansion and quadruple expansion engines are at even greater disadvantage than compound engines, with the result that quadruple expansion engines have dropped out of use for stationary purposes and the use of triple expansion engines is confined almost entirely to large pumping engines.

QUESTIONS

117. Explain fully why a compound engine is more efficient than a simple engine.

118. What are the disadvantages of a compound as compared with a simple engine?

119. Why is the steam in a cylinder drier just before release than it is at the point of cut-off? Explain fully.

120. What happens to the quality of steam in the cylinder when the exhaust valve opens?

121. In any steam engine why is release made to occur before the steam has expanded fully until its pressure is the same as the exhaust pressure?

122. What determines the point of the stroke at which release should occur in a compound engine?

123. What are the advantages of a cross-compound engine with cranks at 90° as compared with a tandem or a cross-compound with cranks at 180°? Explain fully.

124. Why is a receiver necessary on a cross-compound engine with cranks at 90° and not on a tandem-compound engine?

125. Why does the exhaust line on an indicator diagram from a cross-compound engine with cranks at 90° bend upward?

126. What is the effect on the indicator diagram from a cross-compound engine with cranks at 90° if the admission to the low-pressure cylinder occurs after mid-stroke?

127. Could as much power be developed by admitting the high-pressure steam to the low-pressure cylinder directly and disconnecting the high-pressure cylinder entirely as by admitting the high-pressure steam to the high-pressure cylinder directly? Explain your answer fully.

128. Why is more benefit derived from the use of superheated steam in a simple engine than in a compound engine?

CHAPTER XIII

AIR COMPRESSION

99. Air Compressor.—The study of air compression has become very important in recent years by reason of the many uses of compressed air in the industrial world. Compressed air has a greater variety of uses than perhaps any other working substance. Besides its many uses for power purposes, it is used in a large number of manufacturing processes, and in various signalling operations. Compressed air lends itself to a great variety of uses because it is easily and safely handled; it may be transmitted through exposed pipes without the losses which would result from the transmission of steam under similar conditions; it may be stored for considerable periods of time without serious loss; its use is not accompanied by the danger of fire or explosions; and in many operations the exhausted air ventilates the compartment in which it is being used.

Commercial air compressors are made in a great variety of forms and differ from one another in numerous details, but in principle and operation they are similar. A common form of steam-driven air compressor which serves to illustrate the principles and operation of these machines is shown in Fig. 86. This air compressor consists of two principal parts, the air compressor proper, which compresses the air, and a steam engine which runs the compressor. The steam engine which furnishes power for the compressor does not necessarily differ from other steam engines which have been treated in a previous chapter and hence requires nó further attention at this time.

The air compressor proper consists of a piston and cylinder placed in line with the steam cylinder. The piston rod of the steam engine is extended and used for the air compressor piston rod. In this respect the machine resembles a tandem compound steam engine. The barrel of the air compressor cylinder and also parts of the cylinder heads contain hollow spaces, or water jackets, through which cold water is circulated for cooling the cylinder. It thereby exerts a cooling effect upon the air that is

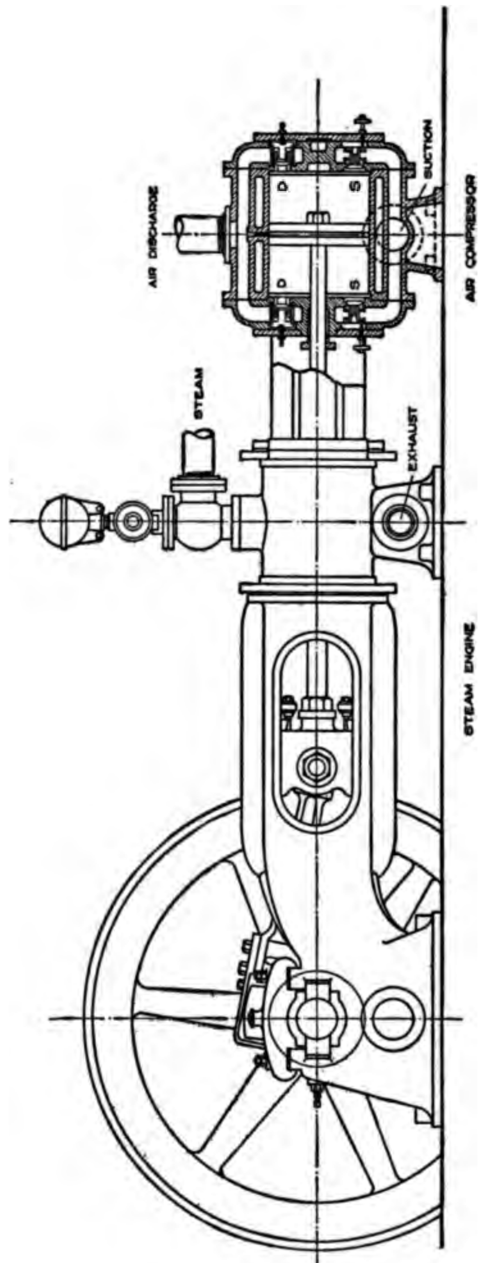
AIR DISCHARGE
STEAM
EXHAUST
SUCTION
AIR COMPRESSOR
STEAM ENGINE
D
S
D
S

Fig. 86.

being compressed. Each end of the cylinder has two valves, one for admitting the air, called a suction or inlet valve, and the other for discharging the compressed air, called the discharge valve.

The valves on the compressor shown in Fig. 86 are of the automatic or spring controlled type. This type of valve is illustrated in Fig. 87 which shows one inlet or suction valve and one discharge valve. These valves are operated by difference in pressure, the weak spring with which they are supplied serving only to hold them closed. The inlet valve opens inwardly and is normally closed. When the piston makes its suction stroke a partial vacuum is created in the cylinder and the atmospheric pressure

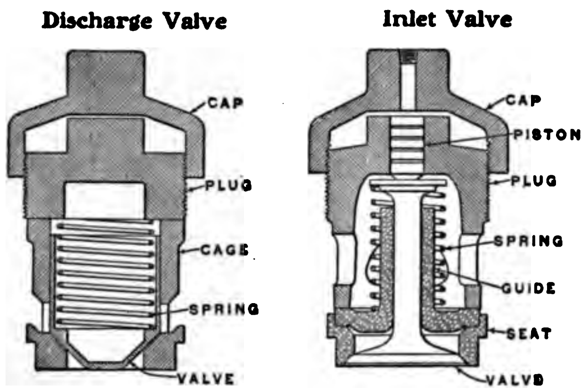

FIG. 87.

acting upon the outside of the valve opens it and allows air to flow into the cylinder. When the piston starts on its compression stroke the spring, aided by the increase of pressure inside the cylinder closes the inlet valve and holds it closed throughout this stroke. As soon as the air in the cylinder has been compressed to a pressure a little above that on the outside of the discharge valve, this valve opens outwardly and allows the compressed air to flow out of the cylinder. Air compressors usually discharge into a large vessel or receiver, hence the pressure in the receiver controls the point at which the discharge valve opens. For most kinds of work the pressure in the receiver is kept practically constant. Many air compressors are fitted with valves which resemble Corliss valves in shape and are operated by mechanical means through levers and rods. Mechanically operated valves open and

close at predetermined points in the stroke and are not dependent upon pressure for their action.

100. Effect of Clearance.—It is important that the clearance volume of air compressors be made as small as possible, hence a type of valve and piston are used which has little or no pockets and the valves are placed as close as possible to the inner edge of the cylinder. A large clearance volume reduces the capacity of a compressor because, at the end of the discharge stroke, the clearance volume is filled with high pressure air which must expand to atmospheric pressure, or less, before a new charge of air can be taken into the cylinder. If the clearance volume is large, a considerable part of the suction stroke will be used in expanding the clearance air, leaving but a small part of the stroke for taking in the new charge of air. This feature in the operation of air compressors may be better understood by a consideration of the compressor indicator diagram which follows.

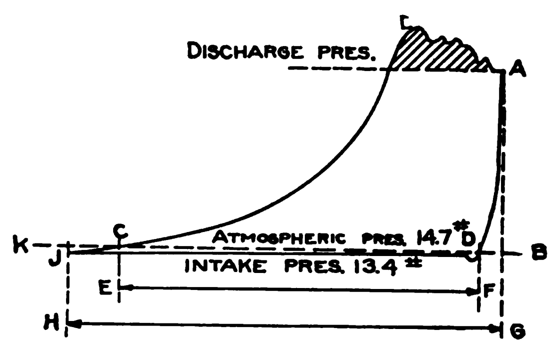

FIG. 88.

An indicator diagram from an air compressor, which shows the changes of pressure and volume in the cylinder during a forward and return stroke of the piston, is shown in Fig. 88. On this diagram the distance *GH* represents the length of the stroke. When the piston is at the end of its stroke represented by *G*, the clearance volume is filled with compressed air at discharge pressure. As the piston moves forward toward H the air in the clearance space expands, as shown by the line *AD*. By the time the piston has moved the distance *BD*, the clearance air has expanded to atmospheric pressure. The piston continues to move forward and the pressure behind it falls below that of the atmosphere, when the inlet valve opens and allows air to flow into the cylinder

for the remainder of the stroke. The pressure in the cylinder during the suction stroke remains a little below atmospheric pressure, the difference being required to hold the inlet valve open against the pressure of its spring.

At J the piston has reached the end of its suction stroke and is ready to make the return or compression stroke. As soon as the piston reaches the end of its suction stroke the inlet valve closes and, as the piston makes the return stroke, the air in the cylinder is compressed along the line JL. It will be observed that the piston moves on the compression stroke a distance JC before the air in the cylinder has been compressed from the suction pressure to atmospheric pressure; hence, while the stroke of the piston is GH, the volume of air compressed, measured at atmospheric pressure is only CD. The theoretical capacity of the compressor at each stroke is the piston displacement HG, but its actual capacity is CD, the difference being $JC+DB$. The reduction in capacity JC is due to the springs on the inlet valves and the reduction, DB is due to the clearance. The strength of the springs on the valves is adjustable to a greater or less extent, but the clearance is a fixed quanity for any given compressor: hence the clearance volume is an important item in compressor construction, and the better makes of compressors have a very small clearance volume.

At L the pressure in the cylinder has been increased enough to open the discharge valve, and during the remainder of the stroke the compressed air is discharged from the cylinder, this pressure being enough above the pressure in the receiver to hold the discharge valve open against the pressure of its spring. At the end of the discharge stroke the spring on the discharge valve causes it to close. The shaded area at the top of the diagram represents the work expended in expelling the air from the cylinder.

101. Horse-power Required.—The work required to compress and discharge the air is represented by the area of the indicator diagram from the compressor cylinder. The indicated horse-power required to compress and discharge the air may be calculated by the formula

$$\text{I.H.P.} = \frac{Plan}{33{,}000}$$

in which $P=$ mean effective pressure from compressor diagram, in lb. per sq. in.

l = length of stroke in feet
a = area of compressor piston, in sq. in.
n = no. of double strokes or revolutions per minute

Nearly all air compressors are double acting, compressing air in both ends of the cylinder, hence the total indicated horse-power is the sum of the indicated horse-power for each end of the cylinder.

Indicator diagrams from both the steam and the air cylinders of an air compressor are illustrated in Fig. 89 in order to show the relation between the horse-power required to compress and discharge the air and the horse-power that must be developed in the steam cylinder to run the compressor. In this compressor the length of stroke and diameter of piston is the same for each cylin-

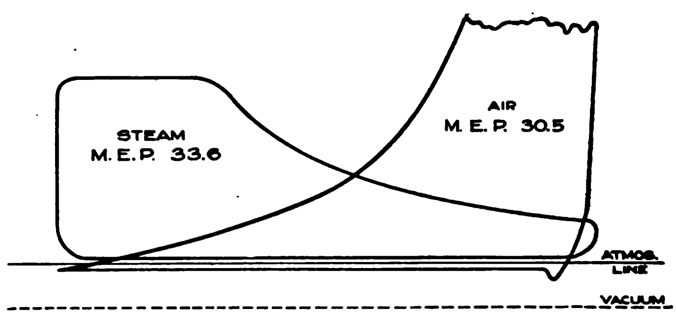

FIG. 89.

der, hence the M.E.P. is a measure of the horse-power from each diagram. It will be observed that the M.E.P. from the steam diagram is 33.6 lb. per sq. in. while that from the air diagram is 30.5, showing that about 10 per cent. more power is developed in the steam cylinder than is used in compressing and discharging the air. The difference between the horse-powers in the two cylinders is used in overcoming the friction of the moving parts of the machine.

102. Types of Air Compressors.—Air compressors may be divided into two main classes according to the arrangement of cylinders. These classes are *straight line* compressors and *duplex* compressors. Compressors in which the steam and air cylinders are in a straight line, similar to that shown in Fig. 86, are called straight-line compressors, and those in which one steam and one air cylinder are placed at each end of the shaft, an arrangement similar to that of the cross-compound steam engine, are called duplex compressors.

The above classes of compressors may be divided into *single-stage* and *multi-stage* compressors. In single-stage compressors the air is compressed from suction to final pressure in a single cylinder. In multi-stage compressors the total range of pressure is divided into two, three, or four parts and each stage of the compression performed in a separate cylinder. In stage compression the discharge from the first cylinder forms the supply for the second, the discharge from the second forms the supply for the third cylinder, and so on. In this respect a single-stage compressor resembles a simple steam engine, and multi-stage compressors resemble multiple expansion engines.

Single-stage compressors are made in both the straight-line and duplex types, the straight-line type being more common. Single-stage duplex compressors are like two straight-line compressors placed parallel to each other and connected to cranks at opposite ends of the shaft, the cranks being located 90° apart. Stage compressors are usually of the duplex type, although two-stage compressors are also frequently made in the straight-line form.

Besides the types of compressors mentioned above, there are those in which the steam engine is compounded. The larger sizes of compressors are invariably made with the steam engine compounded, and usually the air end is multi-stage. Such compressors are almost always of the duplex type, with the steam engine cross-compounded, that is, with one steam and one air cylinder on each side.

Air compressors are also classified according to the manner of driving, as *belt driven*, *motor driven*, and *steam driven*. Of these, the steam-driven ones are most important and are the only ones considered in this chapter.

103. Straight-line Compressors.—A large number of straight-line compressors, both single- and two-stage, are used in small and medium-size compressor plants. This type of compressor is simple in construction, compact, and does not require expensive foundations. It has the disadvantage, however, that it is liable to stop off center, especially if run at low speed. It is not as economical in the use of steam as the duplex type, due to the fact that the power required by the compressor is greatest at the time that the power delivered by the steam cylinder is least. This may be seen from an inspection of Fig. 89, which shows the pressure at any instant in both the steam and air cylinders. It will

be seen from this figure that admission and expansion are occurring in the steam cylinder while compression and discharge are occurring in the air cylinder and that the steam pressure is greatest during the first part of the stroke when the least pressure is needed for compressing the air and also that the steam pressure is least in the last part of the stroke when the air pressure is greatest. This makes it necessary to have a heavy fly-wheel on the straight-line compressor to store up energy in the first part of the compression stroke to be used in the last part when the air pressure is greatest.

104. Duplex Compressors.—The distribution of pressures is much better in duplex compressors because the cranks are placed 90° apart, hence duplex compressors almost always show better steam economy than the straight-line type. They may also be run at lower speeds without being liable to stop. Even if one crank should stop on center the other crank will be off center, and, by having a by pass so that steam may be turned into either cylinder, the compressor may always be started without first turning the fly-wheel. Duplex compressors are more expensive in first cost on account of the greater number of parts and, for the same reason, the friction loss is somewhat greater. They also require more extensive foundations and occupy more room, but even with these disadvantages they are more economical than straight-line compressors.

105. Effects of Different Kinds of Compression.—The character of the compression in an air compressor exerts an important influence upon the amount of power required to run the machine. The compression may vary from isothermal, in which the temperature of the air does not change during compression, to adiabatic, in which the temperature of the air increases a maximum amount during compression. These two methods of compression represent the two extreme conditions under which the compression may occur, and the actual compression may be anywhere between them, depending upon the conditions under which the actual compression occurs. The two extreme conditions of compression are illustrated in Fig. 90 which shows an ideal indicator diagram from a compressor with both the adiabatic and isothermal compression lines drawn so that the amount of work required to compress the air under both conditions may be judged.

Whether the air is compressed isothermally or adiabatically,

the volume of air taken into the compressor at each stroke is represented by KA. If the air is compressed isothermally to 90 lb. per sq. in. its final volume will be DC and the amount of work required to compress and discharge the air is represented by the area $ACDK$. If the air is compressed adiabatically its volume at the end of compression will be DB and the work required is represented by the area $ABDK$.

The amount of work required for compression and discharge is greater for adiabatic than for isothermal compression by an amount equal to the shaded area of this diagram. The volume

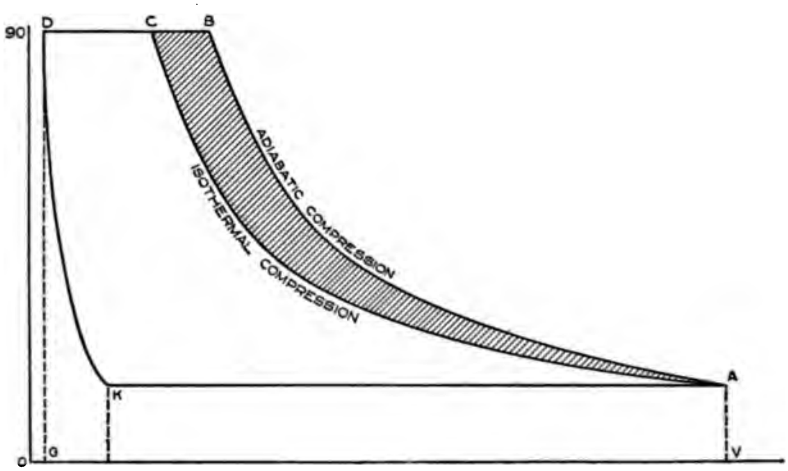

FIG. 90.

of compressed air discharged is also greater for the adiabatic than for isothermal compression by the volume CB. It might be thought, therefore, that there would be no disadvantage in adiabatic compression. It must be remembered, however, that at the end of adiabatic compression the temperature of the air is much higher than at the end of isothermal compression. When the highly heated air resulting from adiabatic compression is discharged into the receiver and pipe lines, it cools to the temperature which it had before compression, and in doing so its volume decreases to the amount DC, the same volume it would have at the end of isothermal compression, in which there is no rise in temperature. Hence, whether the air is compressed adiabatically or isothermally, its final volume by the time it is to be used will be the same, or the volume DC, and, as more work has

been expended in compressing adiabatically than isothermally, there is a decided disadvantage in compressing air adiabatically.

The compression line for an actual air compressor will lie between the isothermal and adiabatic lines, but will usually lie much closer to the adiabatic than to the isothermal, showing that the temperature of the air increases considerably during compression but not quite as much as it would if the compression were adiabatic. The exact shape of the compression line will depend on the amount of cooling which may be secured during compression and upon the speed of the compressor. For isothermal compression the relation between the pressure and volume of the air is such that

$$PV = \text{constant}$$

and for adiabatic compression for air this relation is

$$PV^{1.4} = \text{constant}$$

For ordinary forms of single-state compressors with water jackets and medium speeds the relation between the pressure and volume of the air during compression is about

$$PV^{1.3} = \text{constant}$$

to

$$PV^{1.35} = \text{constant}$$

In general, the greater the value of the exponent of V, the steeper the compression line will be; hence the compression line for an actual compressor lies quite close to an adiabatic, as illustrated in Fig. 91, and there is considerable loss in power from the heat developed in the air during compression.

106. Stage Compression.—The most effective and most common way of reducing the loss of power from the heat developed during compression is to perform the compression in a number of stages, cooling the air between the stages. The way in which this affects the total compression of the air is shown in Fig. 92 which represents the compression of air from atmospheric pressure to 90 lb. per sq. in., being divided into two parts or stages. The number of stages that it is desirable to employ depends upon the final pressure to which the air is to be compressed.

In Fig. 92 the line AB shows the actual compression curve if performed in a single cylinder or stage, the variation between pressure and volume being such that

$$PV^{1.35} = C$$

which is very nearly an adiabatic compression. The line AC is for isothermal compression when performed in a single cylinder or stage. Now suppose the total compression were divided into two parts or stages and the air cooled between stages to its

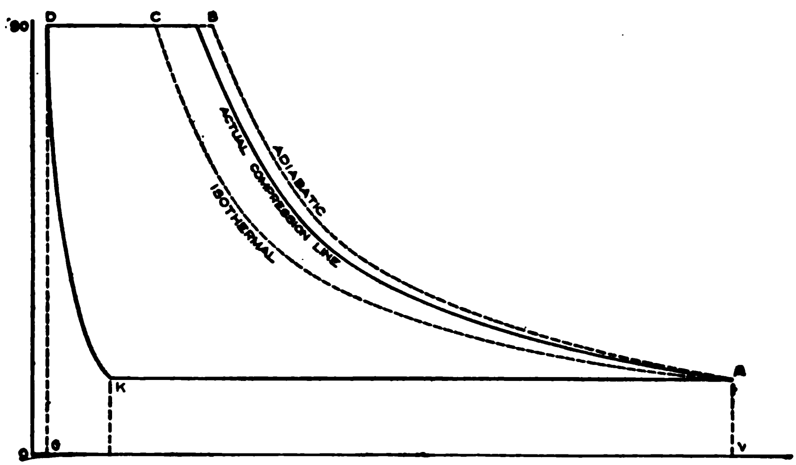

Fig. 91.

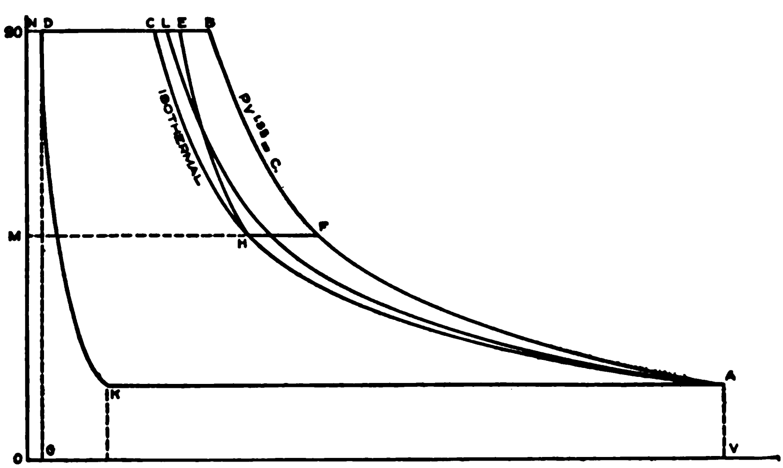

Fig. 92.

original temperature. In the first cylinder the air would be compressed along the line AF until the pressure F is reached. The air, which now has a volume MF, is then discharged from the first cylinder and cooled to its original temperature. Its

volume, after cooling, will be *MH* and this is the volume of air taken into the second cylinder. The compression line for the second cylinder is represented by *HE*, which is very close to an adiabatic.

If an average compression line for the total range of pressure be drawn instead of the two compression lines *AF* and *HE* it will be the line *AL*. The total work of compressing the air in two stages will then be the area *ALDK* while compression in a single stage would require the work *ABDK*. When it is remembered that the final volume of air after cooling in the receiver will be the same in either case it will be seen that considerable saving may be effected by compressing air in stages instead of in a single cylinder. This saving is so pronounced that in compressing air to even as low a pressure as 70 lb. per sq. in. it pays to use a two-stage compressor.

Besides the advantage in the economy of power required to compress air, stage compression also has the advantage that the final temperature of the air is much lower than when the total compression is performed in a single cylinder. This is important because a high final temperature of compressed air sometimes causes an explosion of the oils used to lubricate the cylinder and such explosions are very dangerous.

When air is compressed to 80 or 90 lb. per sq. in. in a single cylinder the final temperature of the air is liable to be near 400° F. unless very effective means are used for cooling it. This temperature is high enough to vaporize and explode some of the poorer grades of oil used for the cylinder lubrication. Explosions of this kind may occur in the cylinder, wrecking the compressor, or they may occur in the receiver after the air has been discharged from the cylinder, thus affecting a larger volume of air and causing even greater damage.

107. Capacity of Compressors.—The capacity of one compressor cannot well be compared with that of another by comparing the number of cubic feet of compressed air which they will deliver per stroke or per revolution, because compressors are used to compress air to widely different final pressures and the volume of compressed air becomes less as the pressure increases. Nor can they be compared upon the basis of the number of cubic feet of air taken into the cylinder per stroke because one compressor may be operated at sea level where the suction pressure is 14.7 lb. per sq. in., while another compressor may be operated at a

high altitude where the suction pressure is much lower and the air has a greater volume per pound. Hence there has arisen the use of the term *free air* which means air at atmospheric pressure, 14.7 lb. per sq. in., and at a temperature of 60° F. By reducing quantities of compressed air to the equivalent number of cubic feet of "free air" the capacities of different compressors may be compared upon the same basis.

Example:

A certain air compressor discharges 60 cu. ft. of air per minute at a gage pressure of 70 lb. per sq. in. This compressor takes its supply of air at 14.7 lb. per sq. in. and at a temperature of 90° F. Another compressor discharges 50 cu. ft. of air per minute at a gage pressure of 90 lb. per sq. in. This compressor takes its supply of air at 13.5 lb. per sq. in. and at a temperature of 70° F. Which of these two compressors has the greater capacity?

Solution:

The first compressor discharges air at an absolute pressure of $70+14.7=84.7$ lb. per sq. in. The absolute temperature of the air taken into the compressor is

$$460+90=550°$$

The absolute temperature corresponding to 60°, the standard temperature for "free air," is

$$460+60=520$$

Therefore, for the first compressor the different quantities may be tabulated as follows:

Actual conditions	$P_1=84.7$	$V_1=60$	$T_1=550$
Standard conditions	$P_2=14.7$	$V_2=?$	$T_2=520$

Placing these quantities in the formula

$$\frac{P_1V_1}{T_1}=\frac{P_2V_2}{T_2}$$

gives

$$\frac{84.7\times60}{550}=\frac{14.7V_2}{520}$$

$$V_2=\frac{84.7\times60}{550}\times\frac{520}{14.7}$$

$$=326.85 \text{ cu. ft. of free air}$$

For the second compressor the absolute pressure at discharge is

$$90+13.5=103.5 \text{ lb. per sq. in.}$$

The absolute temperature at suction is

$$460+70=530$$

Therefore, for the second compressor the different quantities may be tabulated as follows:

Actual conditions	$P_1 = 103.5$	$V_1 = 50$	$T_1 = 530$
Standard conditions	$P_2 = 14.7$	$V_2 = ?$	$T_2 = 520$

Placing these quantities in the formula

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

which gives

$$\frac{103.5 \times 50}{530} = \frac{14.7 \times V_2}{520}$$

$$V_2 = \frac{103.5 \times 50}{530} = \frac{520}{14.7}$$

$$= 345.4 \text{ cu. ft. free air}$$

Therefore the second compressor has the greater capacity.

Some air-compressor manufacturers give the piston displacement of their compressors instead of stating the actual capacity in terms of cubic feet of free air per minute. The piston displacement is always greater than the actual capacity.

108. Effect of Altitude.—Air compressors do not produce the same results at high as they do at low altitudes because the den-

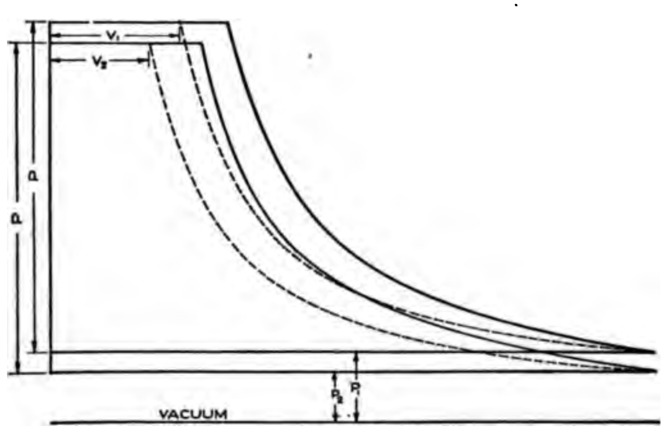

FIG. 93.

sity of air is less and the compressor takes in a smaller weight of air at each stroke, even though the volume of air taken in is the same. The reduction in effective capacity due to altitude is of considerable importance because large numbers of air compressors are used in mining operations where the mines are located at high altitudes.

The reduction in effective capacity due to altitude is shown

by Fig. 93 which illustrates two ideal indicator diagrams for two compressors of the same size and compressing air to the same gage pressure, but working at different altitudes. The volume of air taken in, as shown by the length of the suction lines, is the same for each compressor, and the final gage pressures P are the same. The suction pressure of one compressor is P_1 and for the other P_2. The final volumes of the air are V_1 and V_2 corresponding to the dotted isothermal curves, these volumes being taken as the basis of comparison because they are the ones to which the compressed air will eventually shrink on losing the heat of compression. Although the two compressors take in the same volume of air and compress it to the same gage pressure, it will be observed that the compressor working at the higher altitude, and therefore at a lower suction pressure, has the smaller capacity.

The effect of altitude upon capacity may be illustrated by a simple example. Take the case of two compressors of the same size, one operating under an atmospheric pressure of 14 lb. per sq. in. and the other at 10 lb. per sq. in. (corresponding to an altitude of about 10,000 ft.). If the first compressor is compressing the air 6 times, the final absolute pressure will be $14\times6=84$ lb. per sq. in. which corresponds to a gage pressure of $84-14=70$ lb. per sq. in. To produce the same gage pressure the other compressor must compress to an absolute pressure of

$$70+10=80 \text{ lb. per sq. in.}$$

and the number of compressions corresponding to this pressure is

$$\frac{80}{10}=8$$

For each cubic foot of air taken in, the first compressor will produce $\frac{1}{6}$ cu. ft. of compressed air and the second compressor will produce $\frac{1}{8}$ cu. ft. Hence, the ratio of the outputs of the two compressors will be

$$\frac{1}{8}\div\frac{1}{6}=\frac{3}{4}=.75 \text{ or } 75 \text{ per cent.}$$

Besides a reduction in capacity, more power is required to compress and deliver air at high altitudes than at low ones. The heat developed during compression increases with an increase in the ratio of the final absolute pressure to the initial absolute pressure. As this ratio increases with the altitude, more heat will

be developed by compression to a given pressure at high altitudes than at low ones. This additional heat, as pointed out earlier in this chapter, requires more power for compressing and delivering the air.

109. Efficiency.—There are several ways in which the efficiency of an air compressor may be stated. Theoretically, the volume of air taken into a compressor at each stroke should be equal to the piston displacement, but, as pointed out in discussing Fig. 88, the volume of air actually taken into the compressor at each stroke is always *less* than the piston displacement. The difference is due to the expansion of the air in the clearance space and to the fact that the suction pressure is a little less than atmospheric pressure on account of the tension of the springs on the inlet valves, a small amount of pressure being lost in holding the inlet valves open against the tension of the springs. The ratio of the volume of air in cubic feet actually taken into the compressor, measured at atmospheric pressure, to the piston displacement, in cubic feet, is called the *volumetric efficiency*. The volumetric efficiency of the compressor from which the diagram shown in Fig. 88 was taken is the length of the line EF divided by the length of the line HG, or

$$\text{Volumetric efficiency} = \frac{EF}{HG}$$

The volumetric efficiency measures, in a way, the constructive qualities of the compressor, since it depends on the amount of the clearance volume and the inlet valves, both of which are features of construction. The volumetric efficiency of air compressors varies from 80 to 97 per cent.

The ratio of the work that would be required to compress the air isothermally and discharge it at the receiver pressure, to the work actually required to compress and discharge it at the receiver pressure, is called the *efficiency of compression*. This efficiency shows how nearly the compression comes to a perfect compression, since the isothermal compression represents the best that can be done. The efficiency of compression will vary greatly in different compressors depending upon the type and care used in building the compressor and also upon the provision made for cooling the air during compression. It may be from 60 to 90 per cent.

In order to calculate the efficiency of compression an isothermal curve must first be drawn on the indicator diagram, beginning

at the toe of the diagram and extending up to the discharge pressure. This may be done easily by multiplying together the pressure and volume at the toe of the diagram in order to find the constant in the formula

$$PV = \text{constant}$$

Other points on the isothermal curve may then be found by selecting certain volumes and calculating the corresponding volume from the formula

$$P = \frac{\text{constant}}{V}$$

$$V = \frac{\text{constant}}{P}$$

in which V is the selected pressure.

The ratio of the work performed in compressing the air to the work performed in the steam cylinder, or the work done in driving the machine by other means, is called the *mechanical efficiency.* In a steam-driven compressor it is the ratio of the area of the indicator diagram from the air cylinder to the area of the indicator diagram from the steam cylinder. If there were no friction in the machine this efficiency would be 100 per cent. The difference between the work performed in the steam cylinder and that performed in the air cylinder represents the work lost in friction. In well built air compressors the mechanical efficiency will be from 85 to 90 per cent.

The *total efficiency* of an air compressor is the product obtained by multiplying together its volumetric efficiency, efficiency of compression, and mechanical efficiency. It varies from 50 to 80 per cent.

QUESTIONS

129. Why is it necessary to have a heavy fly-wheel on a straight-line compressor?

130. What is the effect of clearance upon the operation of an air compressor? Explain how the clearance produces this effect.

131. Why is it desirable to have weak springs on the inlet valves of a compressor?

132. How many foot-pounds of work are required to compress one cubic foot of air from atmospheric pressure to 70 lb. per sq. in. gage pressure if the compression is isothermal? How many foot-pounds of work would be required if the compression were adiabatic?

133. It will be observed from Question 132 that there is only a small difference in the amount of work required to compress air isothermally and adiabatically. Why then is there a very decided advantage in compressing air isothermally?

134. Why does a water jacket produce only a small amount of cooling during compression?

135. Why is there a decided advantage in compressing air in stages?

136. What is the effect of altitude upon the operation of a compressor? Explain how altitude produces this effect.

137. The indicator diagram shown in Fig. 89 was taken from an air compressor whose steam cylinder is 20 in. in diameter, air cylinder 22 in. in diameter, and a common stroke of 24 in., running at 110 r.p.m. Calculate the I.H.P. of both the steam and air ends of the compressor. What is the mechanical efficiency of this compressor?

138. Determine from Fig. 89 the volumetric efficiency of the compressor.

139. An air compressor takes its supply of air at a temperature of 96° F. and a pressure of 13.6 lb. per sq. in. and compresses it to 80 lb. per sq. in. gage pressure. This compressor discharges 1200 cu. ft. of compressed air per minute. What is the capacity of the compressor expressed in cu. ft. of free air per minute?

CHAPTER XIV

GAS ENGINES

110. The Gas Engines.—The term gas engine is a name applied not only to engines which use gas as a source of energy, but also to several varieties of engines which use various liquid fuels as a source of energy. Some of these liquid fuels are gasoline, kerosene, alcohol, and various kinds of heavy oils obtained from crude petroleum. All of these kinds of engines, however, are alike in principle because, after all, they are all really gas engines, since those which use liquid fuel vaporize the fuel before using it, which changes it from a liquid to a gas.

Besides the various kinds of liquid fuel used in gas engines there are also various kinds of gaseous fuels used. Some of the gases commonly used are illuminating or ordinary "coal" gas, natural gas, producer gas, water gas, and blast-furnace gas. Space does not permit a description of these various gases here further than to say that they differ greatly from one another in the amount of heat which they liberate when burned. The student is referred to books treating of gas engines for more detailed information about these gases.

The general proportions of engines for using these different gases differ from one another but the different gases undergo the same treatment in the gas engine; that is, the gas is mixed with a quantity of air and drawn into the cylinder. The object in mixing the gas with air is to supply enough oxygen to obtain complete combustion of the gas. Since the various kinds of gas have different compositions, they require different amounts of air to ob-obtain complete combustion. After the mixture of gas and air is taken into the cylinder of the engine it is compressed, ignited and burned. The burning proceeds very rapidly in the intimate mixture of gas and air, and for that reason the burning is called an explosion.

When the gas burns or explodes in the cylinder of a gas engine it liberates a large amount of heat within a small space (since the gas is compressed), and this raises the temperature of the gases

in the cylinder to a very high degree. Since the burning of the gas and liberation of heat takes place almost instantly, the increase in temperature of the gases occurs at practically constant volume; hence the pressure of the gases increases greatly and forces the piston forward, thus causing it to perform work.

The operation of most gas engines which use liquid fuel is the same as those which use gaseous fuel, except in the method of introducing the fuel into the cylinder. In the engine using gas, the gas is drawn directly into the cylinder, while in some engines using liquid fuel the supply of air is drawn through a device called a carburettor, which contains the liquid fuel, such as gasoline. The air in passing over the liquid fuel vaporizes a part of it, changing it into a gas and mixing it with air. The mixture of air and fuel is then drawn into the cylinder and used in a similar manner to that described for engines using gas for a fuel. Only those liquid fuels which vaporize easily such as gasoline, alcohol, and kerosene, can be used in a carburettor.

Those engines using heavier oils which vaporize less easily, generally have the liquid fuel, together with sufficient air, pumped into the cylinder, which it enters in the form of a spray. The spray strikes a hot metal surface in the cylinder and is vaporized. It is then compressed, ignited, and exploded.

It has been shown above that power is obtained from the gas engine by causing gases to explode behind the piston and produce a pressure which moves the piston, the hot gases expanding meanwhile. The series of operations which occur in the cylinder consists of taking in a charge of gas or fuel, compressing and exploding it, then expanding the burnt gases, and finally discharging them from the cylinder. This series of operations is called a *cycle* and gas engines are named according to the number of strokes which the piston makes while this series of operations, or the cycle, is being performed. On this basis there are two kinds of gas engines, called respectively *two-stroke cycle engines,* which require two strokes or one revolution to complete the cycle, and *four-stroke cycle engines,* which require four strokes or two revolutions to complete the cycle. The two kinds of engines are commonly spoken of as simply *two-cycle* and *four-cycle* engines.

111. Four-cycle Engines.—Any gas engine consists of four principal parts. These are a cylinder in which the gas is exploded, a piston for receiving the force of the explosion, a connecting rod for transmitting the motion of the piston to the crank, and a crank

which turns the shaft of the engine. Besides these there are several minor parts for operating the valves and governor.

A small, vertical, four-cycle gas engine is illustrated in Fig. 94. These engines are nearly always single acting, that is, exploding the gas on only one side of the piston, and they are as often made in the horizontal as in the vertical type. The valves of this engine are located in the head of the cylinder. There are two valves, one for admitting the gas, called an inlet valve,

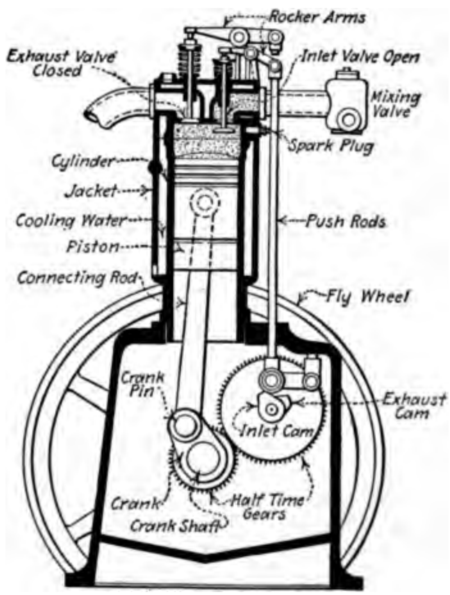

FIG. 94.

and the other for discharging the burnt gas, called an exhaust valve. Both are of the mushroom type with bevelled edges which rest on bevelled seats as shown in the illustration. They are normally held closed by coil springs around their stems and are opened by means of rocker arms connected to push rods. The push rods have rollers on their lower ends which bear against two cams, one to operate the inlet valve and the other one to operate the exhaust valve. Since each valve opens but once in four strokes or two revolutions, the cam shaft is run at half the speed of the engine shaft by two gears, one of which has twice as many teeth as the other.

As the temperature resulting from the explosion of the gas is near 3000° F., which would soon heat the cylinder red hot and destroy its polished surface, the barrel of the cylinder and also the parts of the cylinder head surrounding the valve chambers have a hollow space called a water jacket surrounding them through which water is circulated to prevent the cylinder and valves from becoming overheated. The cylinder is also provided with a spark plug by means of which an electric spark is made in the cylinder at the proper instant and the charge of compressed gas is thus ignited and exploded.

The four-stroke cycle of operations occurs in the following order: At the beginning of the cycle the piston of the engine shown in

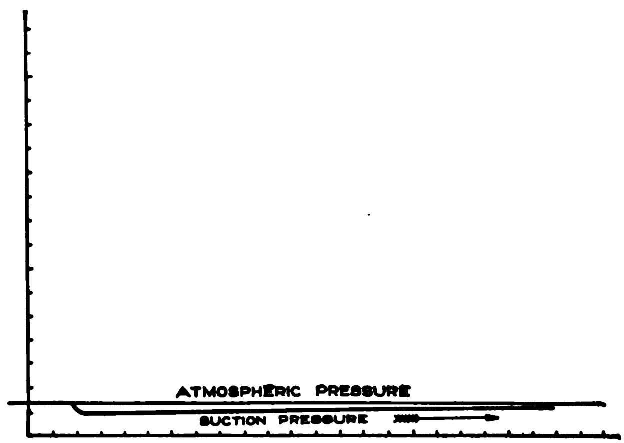

FIG. 95.

Fig. 94 is at the end of its stroke and is at the top of the cylinder. The inlet valve opens at this instant and the piston moves downward, drawing a charge of gas and air through the mixing valve into the cylinder. The inlet valve remains open throughout the downward stroke of the piston. This stroke is called the *suction stroke.* An indicator connected to the cylinder would draw a line on the indicator diagram during the suction stroke similar to that shown in Fig. 95. It will be observed that during the suction stroke the pressure of the gas being drawn into the cylinder is a little less than atmospheric pressure on account of the tendency to create a vacuum by the downward moving piston.

At the end of the downward stroke the inlet valve is closed and remains closed until the next suction stroke. The cylinder is

now filled with a mixture of gas and air and both the inlet and exhaust valves are closed. The piston then moves upward and compresses the mixture or charge into the clearance volume, the pressure of the charge increasing as its volume decreases. This stroke of the piston is called the *compression* stroke. The compression stroke is shown on the diagram in Fig. 96.

Since the speed of gas engines is high, the strokes are made quickly and, although the cylinder is water jacketed, the cooling effect upon the charge is small, hence the compression of the mixture is practically adiabatic. Even though the temperature of the charge is normal room temperature when taken into the cylinder,

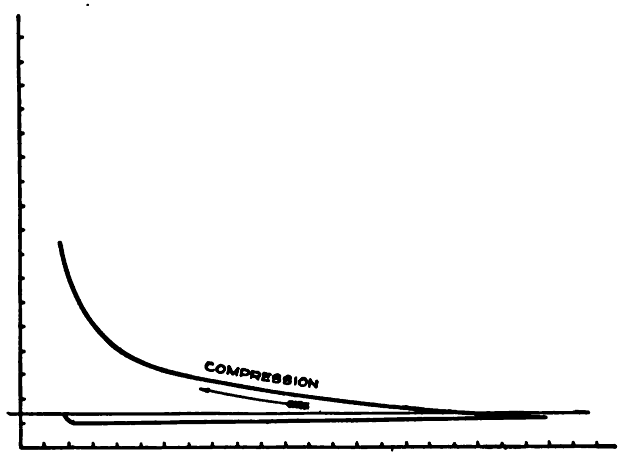

FIG. 96.

its temperautre is greatly increased by adiabatic compression. At the end of the compression stroke the clearance space is filled with a mixture of gas and air at a high pressure and high temperature.

At the beginning of the compression stroke the volume of the mixture in the cylinders is equal to the piston displacement plus the clearance volume, and at the end of the compression stroke the volume occupied by the charge is equal to the clearance volume, hence it must be evident that the pressure reached at the end of the compression stroke, and therefore, also the temperature of the compressed charge, depends upon the size of the clearance space as compared with the piston displacement. The pressure (and temperature) to which compression should be carried depends

upon the kind of fuel used. Different fuels ignite at different temperatures. If the compression pressure is carried too high the fuel will be ignited before the end of the compression stroke. For this reason the ratio between the size of the clearance space and piston displacement is different for engines using different fuels. For gasoline, the clearance space amounts to about 30 or 35 per cent. of the piston displacement.

At the end of the compression stroke (or slightly before) the compressed charge is ignited and it burns almost instantly, or explodes. The burning of the charge liberates the number of heat units contained in the charge, and the presence of this heat fur-

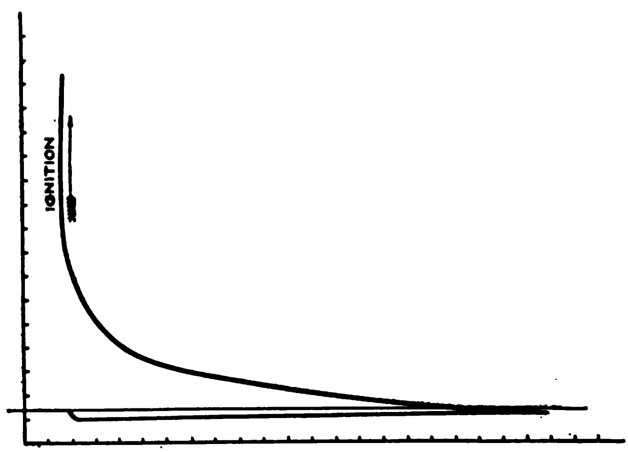

FIG. 97.

ther increases the temperature of the gases in the cylinder, thereby causing a sudden increase in pressure as shown in Fig. 97. Since the increase in temperature at ignition occurs at constant volume, it may be calculated by the following formula:

$$t_2 = \frac{B.T.U.}{WC_v} + t_1$$

in which t_2 = final temperature of the gas after ignition

t_1 = temperautre of gas at end of compression and before ignition

W = weight of gas in cylinder

$B.T.U.$ = heat liberated by the combustion of the charge of gas

C_v = specific heat of the burnt gases at constant volume.

Since the increase in pressure at this point occurs at constant volume, it will be in proportion to the increase in absolute temperature of the gases, or

$$\frac{P_2}{P_1}=\frac{460+t_2}{460+t_1}$$

in which P_1 and P_2 are the absolute pressures before and after the explosion and t_1 and t_2 are the corresponding temperatures on the Farhenheit scale.

It will be observed from the formulas above that a high temperature of the gases after explosion will be obtained when their temperature before explosion is also high. Since the efficiency of

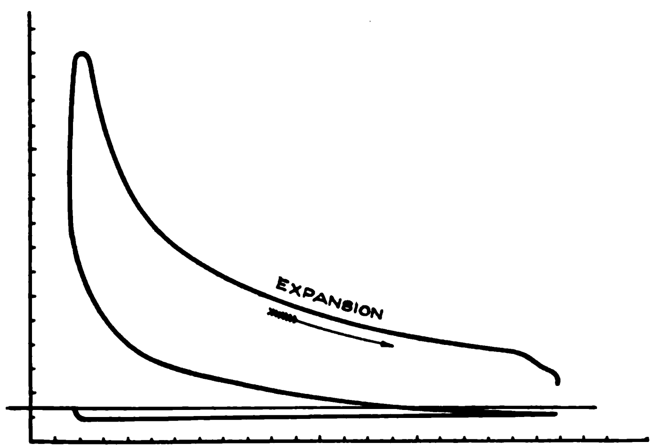

FIG. 98.

the engine depends upon the maximum temperature obtained in the cylinder, it is self-evident that a high compression is an advantage; but, as mentioned before, the kind of fuel sets a limit to the compression pressure that may be used. On account of these facts, the most efficient engines are those which carry the compression as high as possible without causing premature explosion.

The piston is now forced downward upon its expansion or working stroke by the high pressure of the gases behind it. This stroke is sometimes called the *power* stroke, since it is the only one of the four strokes of the cycle in which power is developed, or work is performed upon the piston. As the piston moves downward the volume of the gases is increased and their pressure diminished, as shown in Fig. 98. Just before the end of this

stroke the exhaust valve is opened and the pressure in the cylinder, which is now about 50 or 60 lb. per sq. in., drops to about atmospheric pressure. The expansion of the gases during the working stroke is practically adiabatic for the same reasons that the compression is nearly adiabatic. During the adiabatic expansion of the gases their temperature falls considerably.

The cycle is completed by the next stroke of the piston, which is an upward stroke, during which the exhaust valve remains open and the spent gases are expelled from the cylinder. This is called the *exhaust stroke*, and it is shown in Fig. 99 which also shows the complete indicator diagram for the four-stroke cycle.

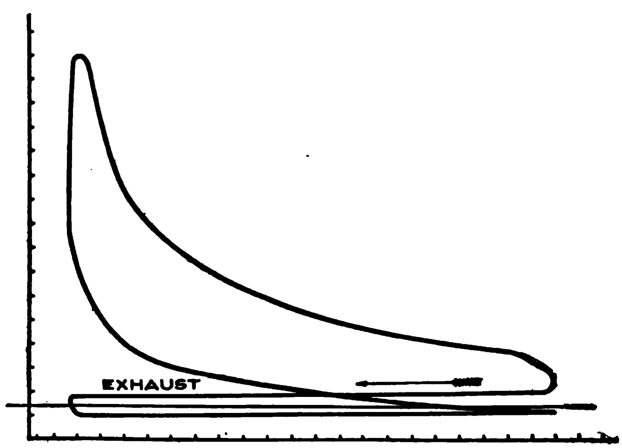

FIG. 99.

112. The Two-cycle Engine.—The two-cycle gas engine is somewhat simpler than the four-cycle engine because there are no inlet and exhaust valves, with their operating mechanism. The piston itself acts as both inlet and exhaust valves by sliding over ports in the side of the cylinder, opening and closing them at the proper time to admit and exhaust the gases.

One form of two-cycle engine that is commonly used for driving launches and other small craft is illustrated in Fig. 100. This engine has the same principal working parts as the four-cycle engine, that is a cylinder, piston, connecting rod, and crank, and the cylinder is water jacketed in a similar manner. This engine is also single acting, like the four-cycle engine. The crank case of the two-cycle engine, however, is entirely enclosed and

made gas-tight so as to form a reservoir or storage space for the gas before it is admitted to the cylinder.

In the two-cycle engine the four necessary operations—suction, compression, expansion, and exhaust—are performed in two strokes or one revolution. Compression and expansion each require a separate and full stroke: therefore the gas must be got into the cylinder and discharged without the piston making a stroke, if the engine is to operate upon a two-stroke cycle. This result is accomplished by first slightly compressing the mixture of gas and air into the crank case, then at the end of the expansion stroke the fresh charge of gas is blown into the cylinder and the spent gas blown out. When the piston moves upward a partial

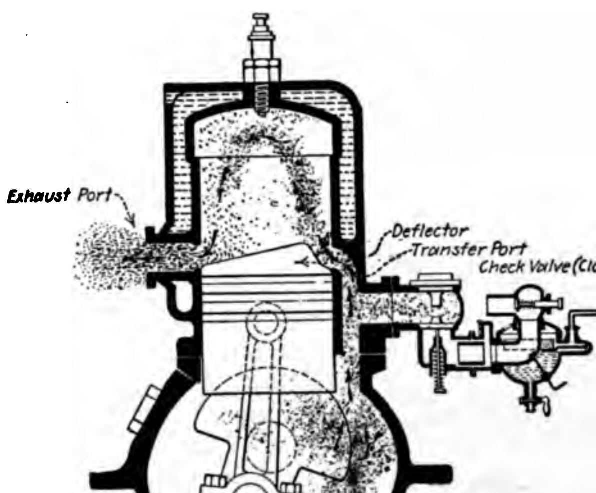

FIG. 100.

vacuum is created in the crank case, and this draws in a charge of gas and air through the check valve. At the end of this stroke the spring on the check valve closes it and the mixture of gas and air is then confined to the crank case. The downward stroke compresses the mixture in the crank case.

For the operations occurring above the piston, the upward stroke is the compression stroke, and the downward stroke is the expansion stroke. Just before the piston reaches the end of the

expansion stroke it uncovers the exhaust port, and the burnt gases, which still have considerable pressure, shoot out of the cylinder. A further downward movement of the piston then uncovers the transfer port, which connects the cylinder with the crank case, and a fresh charge of gas is blown into the cylinder. As it enters it strikes a projection on the piston, called a deflector, which deflects the gas upward and makes it strike the cylinder head. It is then deflected downward and completely fills the cylinder, crowding the spent gases out through the exhaust port. The next upward stroke of the piston first closes the transfer and exhaust ports and then compresses the fresh charge of gas into the clearance space of the cylinder. Ignition occurs at the end of the compression stroke, as in the four-cycle engine, and this is followed by expansion of the highly heated gas. The shape of the indicator diagram from the two-cycle engine is the same as that for the four-cycle engine except that it does not have the two straight lines representing suction and exhaust.

113. Comparison of Cycles.—Both the four-cycle and the two-cycle gas engines have their good and their bad features. The four-cycle engine is more complicated and the moving valves cause trouble at times. Its piston receives only one impulse in four strokes, which causes the speed to be irregular and makes necessary the use of several cylinders or large and heavy fly-wheels to store up energy during the power strokes.

The two-cycle engine has better speed regulation on account of every other stroke being a power stroke, but it, too, requires a fly-wheel to smooth out the speed variations. The spent gases are not expelled from the two-cycle engine as thoroughly as from the four-cycle engine, because there is no separate exhaust stroke. There is also some waste of the fresh gas by blowing through from the inlet to the exhaust opening.

114. Ignition.—There are two common systems of igniting the charge in a gas engine, both depending upon an electric spark inside the cylinder. These two systems are called the *make-and-break* system and the *jump-spark* system. In the make-and-break system there are two contact points inside the cylinder, one of which is movable. The movable contact point first comes in contact with the stationary one and completes, or "makes," the electric circuit. At the proper instant the movable contact point is moved away from the stationary one, breaking the circuit and producing a sharp electric spark, which ignites the compressed

charge of gas. The principal objections to this system is that a movable part extends through the cylinder and is apt to cause trouble.

There are no movable parts extending through the cylinder in the jump-spark system. A stationary spark plug, shown in Fig. 101, is screwed into the cylinder and the electric spark is made between the two points at its end. These points are separated a short distance apart and the wire leading through the plug to the right-hand one is insulated. The other point is connected directly to the metal part of the plug which screws into the cylinder. One wire leading to the plug is connected to the terminal at the outer end of the plug and the other is connected to any part of the engine frame. The spark is made by passing a current of electricity through a high-voltage coil which contains a vibrator. An armature placed on the shaft makes and breaks the circuit at the proper instant, causing a spark to jump between the points of the spark plug. The principal objection to this system is that the spark points are apt to become fouled by a deposit of carbon from the exploding gases.

FIG. 101.

Some engines, especially those using the heavier oils for fuel, depend for ignition upon the high temperature of the metal parts of the cylinder being in contact with the gas at the high temperature produced by compression. One make of engine, the Diesel type, compresses the air separately, the air being compressed in the cylinder to a pressure of about 500 lb. per sq. in. and a temperature of about 1000° F. At the end of the compression stroke the liquid fuel is sprayed into the cylinder and the high temperature of the compressed air ignites it. The oil is sprayed in gradually for about 10 per cent. of the working stroke, hence the combustion is gradual and there is no explosion and sudded rise of pressure as in the ordinary form of gas engine.

115. Governing.—The power of an engine must be controlled to agree with the load under which it is operating; otherwise the engine will speed up when the load is light and slow down when the load is heavy. Since the power of a gas engine is derived from the fuel, the logical way of controlling its speed is to control the supply of fuel. There are various ways of accomplishing this

purpose but they may all be grouped into two methods called the *hit-or-miss* and the *throttling* methods of governing.

The hit-or-miss method of governing consists in causing the engine to fail to take in a charge of fuel as long as the speed is too high. This is accomplished by having the governor connected in such a way that the inlet valve is not opened when the speed is too high, but it opens in the regular manner when the speed is normal or is too low. This method of governing does not give very close speed regulation, especially when used with the four-cycle engine, because in this case, if the engine fails to take in a charge it must make three more strokes before it has another opportunity to receive fuel, and in the meantime the speed may have dropped too low.

The throttling method of governing consists in taking in a charge of gas each time but varying either the amount of the charge or the amount of fuel in the charge to suit the load which the engine is carrying. Somewhat better results are obtained by varying the amount of the charge rather than its strength, because a wide range of speed variation may be controlled in this way, whereas if the charge is weakened very much it will fail to ignite and the charge will be lost. Varying the amount of the charge has the objection that a small charge lowers the compression pressure and thus gives lower efficiency of the engine.

116. Horse-power.—The indicated horse-power of a gas engine may be obtained from the indicator diagram in a similar manner to that described for steam engines and air compressors. The formula used for calculating the I.H.P. is

$$\text{I.H.P.} = \frac{Plan}{33{,}000}$$

in which P = the mean effective pressure in lb. per sq. in. measured from the indicator diagram

l = the length of stroke in feet

a = the area of the piston in sq. in.

and n = the number of *explosions* occurring per minute

In this formula the number of explosions per minute is taken instead of the number of revolutions per minute, because power is developed only when there is an explosion. Since gas engines are generally single acting, the above formula gives the total I.H.P. of the engine.

The brake horse-power is a more useful measure of the power of a gas engine than the indicated horse-power, because it measures the useful output of the engine or the power available at the fly-wheel. The brake horse-power is measured by a friction brake, the same as for a steam engine, and it is calculated in the same way.

A gas engine should be rated according to its brake horse-power, since this is the useful power which it will deliver. If a gas engine were rated at its capacity when taking a full charge each time, it would be developing its maximum power and any addition to the load would stall it, or it would have no overload capacity, as steam engines have. For this reason it is customary to rate a gas engine at $\frac{5}{6}$ of its maximum power, or, if operated with a hit-or-miss governor, when there are 5 explosions in 6 cycles. The maximum power is then $\frac{6}{5}$ of its rated power, or it has an overload capacity of 20 per cent.

117. Efficiency.—It has been pointed out in a previous chapter that the efficiency of the steam engine is rather low, that is, the steam engine changes into work only a small proportion of the energy in the steam supplied to it. On this basis of calculating efficiency the highest efficiency that may be hoped for in the steam engine is only about 20 per cent., and most steam engines show an efficiency considerably lower than this. If we consider the efficiency of the steam engine to be the ratio of the work performed by the engine to the energy in the fuel the efficiency will be very low.

The efficiency of the gas engine is much higher than that of the steam engine, principally because the fuel is burned and the heat developed directly in the engine itself, thus avoiding the losses which would occur in generating the heat at one point and transmitting it to another point to be utilized. As shown before, the efficiency of any engine is proportional to the range of temperature through which it works. The maximum temperature after explosion is about 3000° F. and the temperature of the exhaust is about 1000° F., giving a range of 2000°. Comparing a steam engine on the same basis, the maximum temperature is about 401° F. for 250 lb. per sq. in., and the temperature of exhaust may be as low as 101° F., giving a range of about 300°. It will thus be seen that the gas engine works through a much greater range of temperature than the steam engine, consequently its efficiency is much higher.

The efficiency of a gas engine should be taken as the ratio of

the brake horse-power (expressed in B.T.U.) to the amount of heat energy contained in the fuel, the brake horse-power being taken because this is the useful output of the engine. The horse-power output and the heat energy input should be taken for the same length of time, as a minute or an hour.

The principal losses of energy occurring in the gas engine are the large loss of heat in the exhaust, and the somewhat smaller loss of heat carried away in the jacket water. The large loss of heat through the jacket water is made necessary by the fact that the metal of the cylinder cannot stand the high temperature developed by the burning fuel and it is necessary to cool it to a considerable extent. The rather large amount of heat contained in the exhaust gases is due to their incomplete expansion which leaves them under pressure and at a rather high temperature at the time the exhaust valve opens.

QUESTIONS

140. Describe the two-stroke cycle and the four-stroke cycle.

141. Compare the advantages and disadvantages of these two cycles.

142. Why should an engine using alcohol for fuel be called a "gas engine"?

143. What determines the amount of clearance volume which a gas engine should have?

144. What is the object in compressing the gases supplied to a gas engine?

145. What limits the pressure to which the gases may be compressed?

146. Why is the thermal efficiency of a gas engine greater than that of a steam engine?

147. A card from an $8\frac{1}{4}'' \times 14''$ single-acting four-cycle gas engine has an area of .9 sq. in. and its length is 3 inches. Spring used in the indicator, No. 240. The engine runs 225 R.P.M. and makes 100 explosions per minute. There is a Prony brake on the engine, the length of the brake arm being 63 in. and the net weight on the brake 42 lbs. Find the indicated horse-power and the brake horse-power of the engine.

148. A gas engine uses .9 pounds of gasoline per hour, having a heating value of 19,000 B.T.U. for each brake horse-power developed. The friction loss in the engine is 2700 B.T.U. What is the fuel consumption per indicated horse-power per hour?

149. 16 lbs. of air are mixed with each pound of gasoline used in the above engine. The exhaust temperature is 850° F. and the outside temperature is 90° F. How many heat units are lost in the exhaust per B.H.P. per hour? What per cent. of the heat supplied to the engine is lost in the exhaust? (Assume the specific heat of the exhaust gases the same as that for air.)

150. The jacket water enters at a temperature of 60° F. and leaves at a temperature of 150° F. The weight of the jacket water is 85 lbs. per B.H.P. per hour. How much heat is carried away in the jacket water per B.H.P. per hour? What per cent. of the heat supplied to the engine is lost in the jacket water?

CHAPTER XV

REFRIGERATION

118. Process of Refrigeration.—The method of keeping food cool in the ordinary household refrigerator is familiar to all of us. The cooling is done by a block of ice placed in one part of the refrigerator, the food being in another part. In some refrigerators the interior compartments are arranged so there will be a definite circulation of air; the air coming in contact with the ice is cooled and drops to the bottom of the refrigerator. It then rises to the top again as it gradually becomes warmer.

Refrigeration, or cooling, is the reverse of heating. In heating, a body at a high temperature such as a radiator gives up heat; in cooling, a body at low temperature such as a block of ice absorbs heat. The block of ice in a refrigerator absorbs heat from the air and food and, since the ice is usually at 32° F., its melting point, a part of it melts when it absorbs heat. If the ice happens to be below 32° F., the heat which it absorbs first raises its temperature to 32° F. and then begins to melt it. The water resulting from the melting ice has a temperature of 32° F. but in trickling over surfaces of the refrigerator and being drained out of it, it comes in contact with the air inside the refrigerator, and its temperature is raised a few degrees above 32° F.

The latent heat of ice is 142 B.T.U. per pound, so that for every pound of ice melted 142 B.T.U. must be absorbed. The total heat absorbed from the refrigerator will be the sum of that absorbed in heating the ice up to its melting point, in melting the ice, and in heating the water resulting from the melting ice from 32° up to the temperature at which it leaves the refrigerator. For example, a 50-pound block of ice having a temperature of 24° F. is placed in a refrigerator and in a certain length of time $2\frac{1}{2}$ pounds of the ice are melted, the water resulting from the melting ice leaving the refrigerator at a temperature of 40° F. Since the

specific heat of ice is .5, the amount of heat absorbed in raising the 50-pound lump from 24° to 32° is

$$\begin{aligned} & .5\times50\times(32-24) \\ = & .5\times50\times8 \\ = & 200 \text{ B.T.U.} \end{aligned}$$

Ordinarily ice has a temperature of 32° F. unless it is used on a very cold day, when its temperature may be below 32° F. In melting, the ice absorbs

$$2\tfrac{1}{2}\times144=360 \text{ B.T.U.}$$

Since the specific heat of water is 1.0, the amount of heat absorbed by the water when its temperature increases from 32° to 40° is

$$\begin{aligned} & 1.0\times2\tfrac{1}{2}(40-32) \\ = & 1.0\times2\tfrac{1}{2}\times8 \\ = & 12 \text{ B.T.U.} \end{aligned}$$

and the total heat absorbed from the refrigerator in this length of time is

$$200+360+12=572 \text{ B.T.U.}$$

Even though refrigerators are built of more or less non-conducting substances there is a constant leakage of heat through them from the outside, where the temperature is higher, to the inside, where the temperature is lower. The heat that leaks into the refrigerator in this way warms the air inside, and, in cooling the air, the ice absorbs this heat. Besides the leakage of heat through the walls of the refrigerator, there are other sources of heat such as the leakage of warm air into the refrigerator when the doors are opened, and the placing of comparatively warm foodstuffs in the refrigerator to be cooled.

Ice has been used to a considerable extent in the past for cooling cold-storage compartments, but this method of refrigeration is not well adapted to this purpose because many kinds of food stuffs require a lower temperature than can be produced by melting ice. At the present time ice is used in a few cold-storage houses for keeping butter and eggs, but the majority of them are cooled by some mechanical system of refrigeration. Ice is used extensively at the present time for cooling refrigerator freight cars in shipping meat, fruit, and vegetables. For this purpose the ice is placed in a compartment in one end of the car, and the

food-stuffs fill the balance of the car. The walls and doors of the car are lined with non-conducting material to reduce the leakage of heat into the car.

Temperature lower than 32° F. may be obtained by mixing common salt with cracked ice. The theory of this is that the presence of the salt lowers the melting point of the ice, hence, the ice being at 32°, is considerably above its melting point and melts very fast. In melting, the ice must absorb its latent heat, therefore the rapid melting of the ice caused by the presence of salt produces a rapid cooling effect. A familiar example of cooling by this method is found in the ordinary ice-cream freezer where the cream to be frozen is placed in a tin vessel and this is placed in the center of an outer vessel, usually of wood. The space between the two vessels is then filled with a mixture of salt and cracked ice which produces a temperature low enough to freeze the cream.

Mixtures of various kinds of salt with ice are used for producing low temperatures for experimental purposes, but the use of this method is not practical for cooling on a large scale for commercial purposes, on account of the cost of the salts used in making the freezing mixture. The fact that ice alone will not produce temperatures below about 32° F. and the excessive cost of making freezing mixtures have brought about the development of various mechanical systems of refrigeration by means of which lower temperatures than 32° F. may be produced. These systems are now very widely used for refrigerating cold storage compartments and for making ice. The two principal systems of mechanical refrigeration are known as the *compression system* and the *absorption system.*

119. Compression System.—There are three types of compression refrigeration systems differing from each other in the substances used for producing the refrigerating effect. These substances are ammonia, carbon dioxide, and sulphur dioxide. The ammonia system is used almost exclusively in commercial work, for reasons which will be discussed later, and this is the system which will be described here.

A simplified diagram of an ammonia compression refrigeration system is shown in Fig. 102. This system consists of only three parts: an ammonia compressor, *P*, a condenser, *K*, and an evaporator or cooler, *V*. The compressor resembles an air compressor in construction, having spring-controlled suction and discharge valves for each end of the cylinder. The compressor is

driven by a steam engine, or other source of power, not shown in the diagram. The compressor shown here is double acting, although many of them are built single acting.

The form of condenser shown here consists of a coil of pipe immersed in a tank of water. A constant stream of water is passed through the tank, entering at A and leaving at B. The cooler also consists of a coil of pipe in a tank but in this case brine,

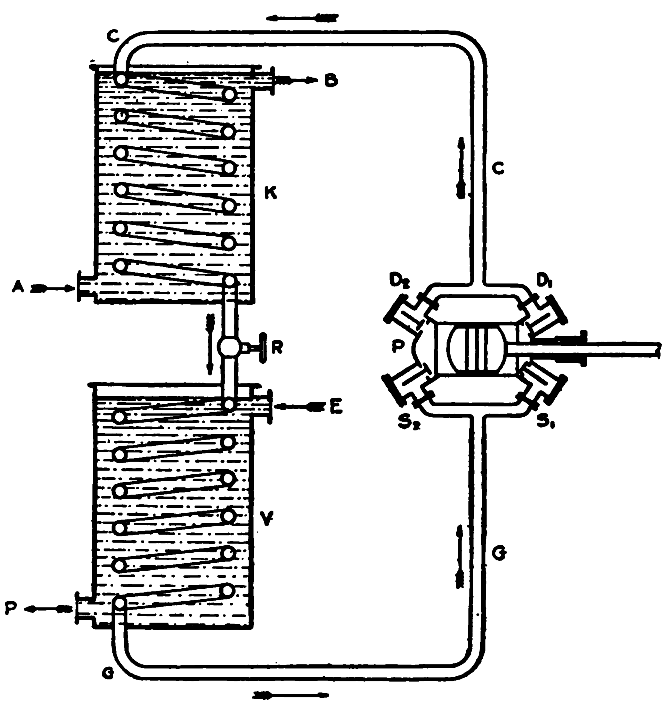

FIG. 102.

which has a lower freezing point, is circulated through the tank instead of water, the brine entering at E and leaving at P.

The path of the ammonia through the system is indicated by the arrows in Fig. 102. Starting at the compressor, saturated ammonia vapor is compressed to a high pressure and discharged into the condenser through the pipe C. Suppose the compressor delivers the ammonia to the condenser at a gage pressure of about 137 lb. per sq. in. Reference to the table of "Properties of Saturated Ammonia Vapor" in Chapter IX will show that the boiling

temperature of ammonia at this pressure (152 lb. per sq. in. absolute) is 79.3° F.; therefore, if the ammonia vapor is cooled below this temperature, it will condense and form liquid ammonia. A supply of water cooler than 79.3° F. is easily obtained; hence the ammonia may be liquefied in the condenser by passing it into a coil immersed in running water. The liquid ammonia then collects in the bottom of the coil, above the valve *R*. The liquid ammonia occupies much less space than the vapor from which it was formed, hence the pressure in the condenser would drop if it were not for the fact that the compressor runs continuously, pumping ammonia into the condenser and keeping up the pressure. The bottom of the condenser, therefore, contains liquid ammonia at a gage pressure of 137 lb. per sq. in. and a temperature a little below its boiling point, 79.3° F.

The suction side of the compressor is connected with the evaporator or cooler, *V*, by the pipe, *G*, and the pressure in the evaporator will be the same as the suction pressure of the compressor, say about 23 lb. per sq. in. gage.

The valve *R*, called an *expansion valve*, is placed between the condenser and the evaporator to regulate the flow of ammonia into the evaporator. The pressure above this valve is comparatively high, about 137 lb. gage, and below the valve it is comparatively low, about 23 lb. gage. The boiling temperature of ammonia at 23 lb. gage (38 lb. absolute) is 10° F. and, as the ammonia in the condenser is considerably above this temperature (79.3° F.), any ammonia passing the expansion valve, *R*, boils and is quickly evaporated. Since the liquid ammonia is at 79° F. and its boiling point is now 10° F., some of it will immediately evaporate and cool the rest of the liquid to 10° F. The remainder must then absorb its latent heat from some other source before it can evaporate. The ammonia takes up this heat from the brine which surrounds the coil in the evaporator, and in so doing reduces the temperature of the brine. The cooled brine is then pumped through pipes located in the compartments to be cooled, where it takes up heat, and is circulated back through the evaporator to be cooled again.

The ammonia in the evaporator is in the form of a vapor at low pressure and temperature, and at each stroke of the compressor some of this vapor is taken into the cylinder and compressed to a high pressure. The office of the compressor is, therefore, merely to circulate the ammonia and to raise its pressure so the heat

can be removed from the ammonia at a higher temperature, the real refrigerating effect being produced by passing the ammonia through the expansion valve.

The pressures and temperatures stated above have been used only for illustration. The actual pressures to be used would depend on the conditions at the plant and would be varied to suit the temperature of the supply of water for the condenser and the temperature desired in the evaporator. The discharge pressure must always be high enough to produce a temperature above that of the condensing water, in order that the ammonia may be liquefied in the condenser. The suction pressure must be regulated to suit the lowest temperature desired. The suction and discharge pressures are controlled by the speed of the compressor and by the amount of ammonia which is allowed to pass the expansion valves, and these are regulated to suit the conditions under which the plant is operating.

The refrigerating system described above and illustrated in Fig. 102 is called an *indirect system* because the refrigerating effect is carried to the room to be cooled in an indirect manner, that is, by first cooling brine and then carrying the cooled brine to the point desired. A *direct system* is one in which the cooling coils are located directly in the room to be cooled and the refrigerating effect applied directly.

120. The Absorption System.—If ammonia is brought in contact with cold water, the water will absorb large quantities of it. It is possible for water to absorb as much as 1000 times its volume of ammonia vapor. Warm water, however, will absorb only a small quantity of ammonia. The amount of ammonia that may be held in solution depends upon the temperature of the water, being large for a low temperature and smaller for a higher temperature. It thus happens that if ammonia vapor is brought in contact with cold water the ammonia will be absorbed and if the water is afterward heated the ammonia will be driven out of solution.

The above peculiar properties of ammonia form the basis of the absorption system of refrigeration. The absorption system differs from the compression system in not having a compressor, but it resembles the compression system in having a condenser, cooler, and expansion valve. The duty of the compressor is performed, in the absorption system, by two pieces of apparatus called respectively an *absorber* and a *heater*. In the absorber

the low-pressure ammonia vapor coming from the cooler is brought into contact with cold water or a weak solution of ammonia in cold water, which absorbs the ammonia. The solution, which is now strong, is then passed into the heater where it is heated by means of steam coils. Heating the strong solution drives out the ammonia vapor which is then passed into the condenser and liquefied the same as in the compression system. The pressure

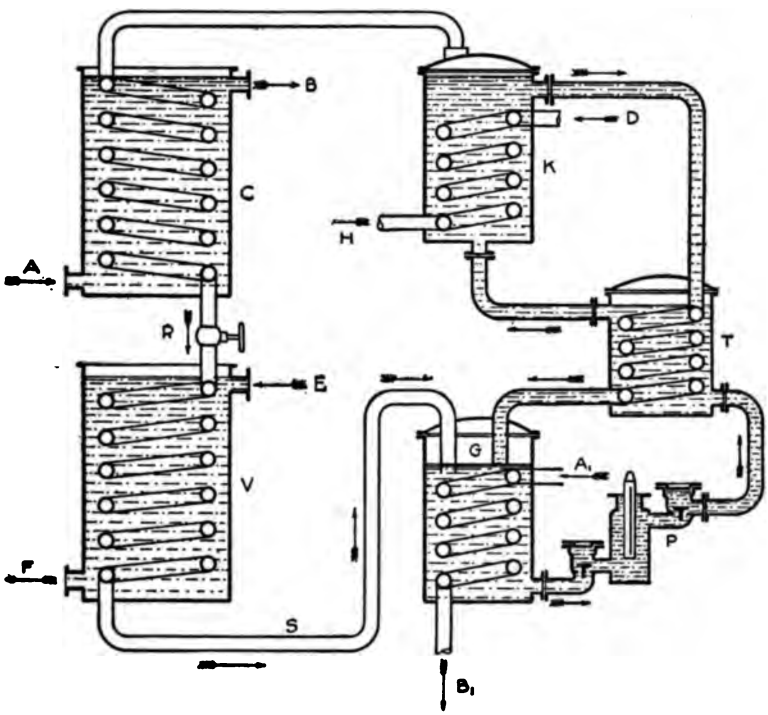

FIG. 103.

of the ammonia vapor driven out of solution in the heater depends upon the temperature to which the strong solution is heated, since the pressure of ammonia vapor depends upon its temperature.

An absorption system of refrigeration is shown diagrammatically in Fig. 103. The condenser is shown at *C*, the expansion valve at *R*, and the brine cooler at *V*, these parts of the system being the same as in the compression system. The absorber is shown at *G*. The ammonia vapor coming from the cooler is passed through the pipe *S* into the absorber, where it comes in contact

with the weak solution and is absorbed. The absorber contains a coil, AB, through which cold water flows in order to cool the weak solution, thereby enabling it to absorb a larger quantity of ammonia vapor. The strong solution is drawn from the bottom of the absorber by the pump, P, which forces it through the vessel, T, and into the heater, K. The heater contains a steam coil, DH, for heating the strong solution and thus driving out the ammonia vapor. Tha ammonia vapor then passes into the condenser, is liquefied, and passes through the expansion valve into the cooler, the same as in the compression system. This completes the circuit of the ammonia through the refrigerating system.

The piece of apparatus marked T is called an *exchanger*, and, while it is not essential to the absorption system, it is always used because it saves heat which would otherwise be wasted.

After the strong solution is heated in the heater to drive out the ammonia, the resulting weak solution is carried back to the absorber to take up more ammonia. When the weak solution leaves the heater it is at a high temperature and it must be cooled before it will absorb more ammonia. On the other hand, the strong solution leaving the absorber is at a low temperature and must be heated before the ammonia is driven out; hence there is a good opportunity for an exchange of heat between the weak and strong solutions. This is done in the exchanger, T. The hot weak solution is passed through a coil in the exchanger on its way to the absorber. The cold strong solution, on its way to the heater, is pumped through the exchanger where it comes in contact with the coil containing the hot weak solution. The hot weak solution thus gives up heat to the cold strong solution, and reduces the amount of cooling required in the absorber and the amount of heating required in the heater.

The absence of complicated machinery in the absorption sys tem of refrigeration makes this system simpler than the compression system, and for the same reason reduces the amount of labor required to run it. The ammonia pump and a pump for circulating brine (in the indirect system) are the only pieces of machinery required, and these are simple and easily operated and kept in repair. The exhaust steam from the pumps may be used in the heater, the extra amount of steam required being supplied at reduced pressure from the boiler which furnishes steam for the pumps.

The heater, exchanger, and absorber are usually built in the form of cylinders which may be placed close together, and, as they occupy only small space, all of the apparatus, except the condenser and cooler, may be grouped in one room and one man can care for them. The condenser and cooler may also be placed with the other apparatus in the indirect system.

While the forms of condenser and cooler shown in Figs. 102 and 103 consist simply of a tank containing a coil, in practice they are usually constructed of a series of double pipes, a small one placed inside a larger one so there will be a space between the pipes. In the condenser the ammonia flows through the space between the two pipes and the water through the small inner pipe. In the cooler the ammonia flows through the small inner pipe. This form of condenser or cooler is very efficient because large surfaces for the transfer of heat are obtained within a small space and the water or brine flowing in a thin stream over these surfaces effects a rapid transfer of heat.

121. Other Compression Systems.—Both of the refrigerating systems just described use ammonia as the refrigerating agent, but it has been previously mentioned that either carbon dioxide or sulphur dioxide may be used as the refrigerating agent in a compression system.

A compression system of refrigeration using either carbon dioxide or sulphur dioxide is exactly the same in principle as one using ammonia. All of these systems consist of the same apparatus and the refrigerating agent goes through the very same cycle of operations, being compressed in a compressor, liquefied in a condenser, and expanding through an expansion valve into a cooler. However, there is a difference in these systems in the strength of the apparatus due to the different pressures required, and also in the size of the compressors due to the amount of refrigerating agent that must be circulated to produce a certain cooling effect. These differences are best understood by comparing the properties of the different refrigerating agents.

It is convenient to compare refrigerating agents on the basis of the highest and lowest temperatures that must be carried. The highest temperature is that reached after compression, and it depends upon the temperature of the condensing water, for it must always be somewhat above the temperature of the condensing water in order to be liquefied in the condenser. The lowest temperature is that reached in the cooling coils, and this tempera-

ture must be controlled according to the cooling effect desired. In comparing ammonia, carbon dioxide, and sulphur dioxide we will assume a highest temperature of 68° F., since this is a little above the temperature of the ordinary supply of condensing water; and a lowest temperature of 14° F., since this is a common temperature used for cold storage work.

The following table shows the properties of the three refrigerating agents mentioned above for these two temperatures:

	Temp.	Absolute pressure per lb. per sq. in.	Latent heat B.T.U.	Heat of the liquid B.T.U.	Volume of 1 lb. in cu. ft.
Ammonia	68°	124.7	514.7	39.9	2.377
	14°	41.71	561.2	−19	6.72
Carbon dioxide	68°	826.4	66.5	23.08	.083
	14°	385.4	110.7	− 9.0	.229
Sulphur dioxide	68°	47.61	152.5	12.03	.171
	14°	14.75	168.2	− 5.69	.527

Since the cooling is performed by the evaporation of the refrigerating agent, the number of heat units transferred per pound of agent depends upon its latent heat. In this respect ammonia has a great advantage over either carbon dioxide or sulphur dioxide because for every pound of ammonia circulated through the system the cooling effect obtained will be 561.2 B.T.U., while the circulation of a pound of carbon dioxide will produce only 110.7 B.T.U., and sulphur dioxide only 168.2 B.T.U. To produce the same cooling with carbon dioxide as with ammonia would require the circulation of 5.07 pounds of carbon dioxide as against one pound of ammonia; and for sulphur dioxide 3.34 pounds as against one pound of ammonia.

The pressures that must be carried in a refrigerating system are important because the compressor must be built strong enough to carry the necessary pressure, and this affects its cost. In order to secure a temperature of 68° F. at the end of compression, the absolute pressure of carbon dioxide must be 826.4 lb. per sq. in., of ammonia 124.7 lb. per sq. in., and of sulphur dioxide 47.61 lb. per sq. in. The extremely high pressure required for carbon dioxide requires a very heavy construction of the machine and piping. In warm climates where the temperature of condensing water is higher the pressure necessary for carbon dioxide sometimes goes as high as 1000 lb. per sq. in. The pressures required

for ammonia and sulphur dioxide are not very high and do not require extra heavy construction.

The lower pressures to be carried are of importance as these should never go below atmospheric pressure on account of the leakage of air into the system, which causes trouble. With ammonia, a temperature of 14° F. may be secured with a pressure of 41.71 lb. per sq. in. and considerably lower temperatures may be secured without lowering the pressure below that of the atmosphere. The same is true of carbon dioxide, which gives a temperature of 14° F. with a pressure of 385.4 lb. per sq. in. With sulphur dioxide, on the other hand, the temperature cannot go much below 14° F. without reducing the pressure below that of the atmosphere and giving an opportunity for the leakage of air into the system.

The piston displacement and size of the cylinder of the compressor depend upon the volume of one pound of the refrigerating agent at its lowest temperature, and upon the number of pounds that must be compressed to secure a certain cooling effect. Since the weights of carbon dioxide and sulphur dioxide which must be compressed in order to secure the same cooling effect as with one pound of ammonia are respectively 5.07 and 3.34 pounds, the relative piston displacements are for

Ammonia	$1 \times 6.72 = 6.72$ cu. ft.
Carbon dioxide	$5.07 \times .299 = 1.16$ cu. ft.
Sulphur dioxide	$3.34 \times .527 = 1.76$ cu. ft.

It thus appears that a much smaller compressor may be used for carbon dioxide and sulphur dioxide than for ammonia. In the case of carbon dioxide this compensates, in a measure, for the extra heavy construction required.

The extremely high pressures that must be carried with carbon dioxide and the low suction pressures necessary with sulphur dioxide when low temperatures are to be obtained have operated to the disadvantage of these refrigerating agents so that nearly all of the compression systems used in America employ ammonia as the refrigerating agent.

122. Compressed-air Refrigerating Machines.—In studying the compression of air (Chapters VIII and XIII) it has been shown that an air compressor delivers air at a very high temperature. It has also been shown that when compressed air is expanded it experiences a large drop in temperature. These

principles have been made use of in producing a refrigerating effect by using compressed air.

A compressed-air refrigerating machine would consist of three cylinders, if steam driven: one steam cylinder for driving the machine and two air cylinders, one for compressing the air and another for expanding it. In operation, air is compressed in the compressor cylinder to a high pressure, which also brings it to a high temperature. The hot compressed air is then carried through pipes to a cooler which consists of a cylindrical vessel containing a large number of small pipes carrying the compressed air. Cold water is passed through the cooler around the pipes and cools the compressed air. The compressed air, which is now cooled, is passed into the expanding cylinder where it is expanded to a lower pressure, thereby lowering its temperature and, at the same time, the power derived from the expanding air assists in running the machine. In this way, both the steam and expanding cylinders perform work on the main shaft which drives the compressor piston. The air, which is very cold after expansion, is then carried through well-insulated pipes to the point where the refrigerating effect is desired. It is then passed through coils of bare pipe and cools the surrounding air, after which it is carried back to the compressor cylinder to be used over and over again.

In the compressor cylinder the air is usually compressed to a pressure of about 210 lb. per sq. in. and expanded, in the expanding cylinder, to a pressure of about 60 lb. per sq. in. By using these pressures the temperature of the air after expansion is about 60° F. below zero, and the pipes carrying the air to the refrigerated compartments may be small, which reduces the loss of heat from them.

Attempts have been made to operate air refrigerating machines by discharging the expanded cold air directly into the cold-storage compartment and then taking the supply of air for the compressor directly from the cold-storage compartment. In doing this, however, the air takes up moisture from articles in the cold-storage compartment and this is later deposited as frost in the pipes and soon clogs them. A further objection to this system is that the air cylinders must be very large to accommodate the air at low pressure and the loss from friction in the machine is very large. The dense air machine described above overcomes both of these objections by circulating the same air over and over again through pipes and by using higher pressures.

It has been suggested that the air refrigerating machine might also be used as a warming machine by reversing the cycle of operations in it, thus enabling one to use the same machine for warming a house in winter and for cooling it in summer. When operated as a warming machine the air would first be expanded to a low pressure and low temperature in the expanding cylinder. It would then be passed through a coil of pipe located outside the house where it would be warmed by the outside air since the air in the coil would have a much lower temperature. The air, whose temperature has now been increased, is next passed into the compressing cylinder where it is compressed and its temperature raised to any desired degree. It is then passed through radiators or coils of pipe in the rooms to be warmed, after which it goes to the expanding cylinder and the cycle is repeated. This device would really be a heat pump, pumping heat from the outside of the house to the inside. These machines have not, however, been developed to a commmercial basis.

123. Production of Low Temperatures.—The principles of the air refrigerating machine have been applied in the production of extremely low temperatures. These principles depend upon compressing air, or other gas, to very high pressures, then cooling the air to normal temperature, and expanding it, causing its temperature to fall still further.

One of the most common and interesting applications of this method of producing low temperatures is in the manufacture of liquid air, which requires a temperature of about 350° F. below zero. Even lower temperatures than this have been obtained in the liquefaction of other gases.

The principles of an apparatus for making liquid air are shown in the diagrammatic sketch of Fig. 104. The air compressor is shown at *P*, being driven from some outside source of power such as a steam engine. The compressor is usually of the four stage type and compresses the air to about 3000 lb. per sq. in., the air being cooled between stages to prevent too great an increase in temperature. From the compressor the air is carried to the cooler *M*, where it is passed through a coil of pipe surrounded by cold water. This cools the air to practically the temperature of the water, its pressure remaining at about 3000 lb. per sq. in. From the cooler, the compressed air is carried through the small pipe *BC* to the economizer *N*. The economizer consists of a coil of two pipes one of which is a continuation of the small pipe *BC*. This

passes inside a larger pipe and is concentric with it. At the bottom the two pipes separate, but both enter the small iron vessel T, the smaller pipe being provided with a needle valve R, for regulating the flow of air. The compressed air flows through the inner pipe and in passing through the needle valve it expands adiabatically to a low pressure. In expanding, the air experiences a large drop in temperature. The cold low pressure air then flows through the larger pipe surrounding the compressed air tube and thereby cools the compressed air to almost its own temperature. The low-pressure air passes back to the compressor through the

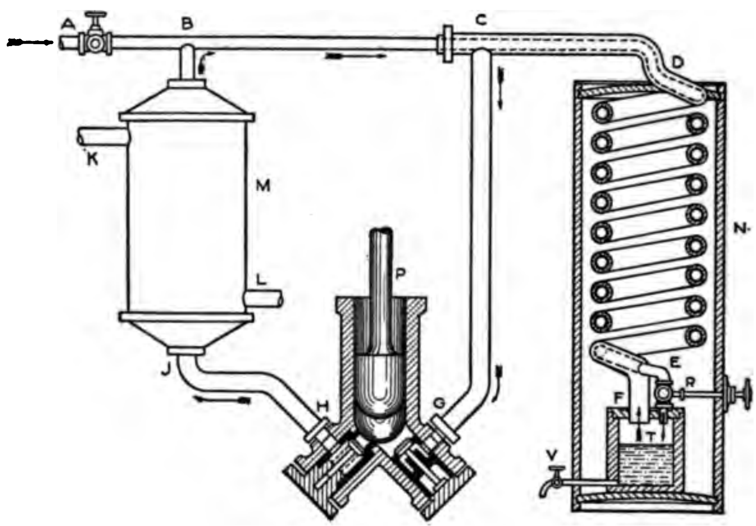

FIG. 104.

pipe CG and goes through the cycle again and again. The chilling of the air in the economizer and its expansion through the needle valve R soon reduces its temperature to the liquefying point. That part of the air which is liquefied collects in the bottom of the chamber T, the remainder passing on to the compressor. The liquid air may then be drawn off through the valve V.

Since the economizer is subjected to extremely low temperatures it is necessary to insulate it carefully in order to prevent the leakage of heat into it, which would throw additional work upon the compressor. Insulation is provided by surrounding the economizer coils with a wooden casing, as shown in Fig. 104, and packing the space around the coils with sheep's wool.

124. Capacity and Efficiency.—Since refrigeration was formerly done with ice, it has become customary to compare the capacity of mechanical refrigerating systems with the cooling effect of ice. The latent heat of melting ice is 142 B.T.U. per pound or $2000 \times 142 = 284{,}000$ B.T.U. per ton. That is, when one ton of ice melts it absorbs 284,000 B.T.U. The capacity of refrigerating machines is expressed in tons. One ton of refrigeration is the transfer of 284,000 B.T.U. in 24 hours, and is the same cooling effect as would be obtained by the melting of one ton of ice in 24 hours.

Stating the capacity of a refrigerating machine in tons of refrigeration does not mean, however, that it will make that many tons of ice. Its ice-making capacity will be considerably less than its rated capacity on account of the losses of heat throughout the system and because the water from which the ice is made must be reduced in temperature to the freezing point. On account of these losses the actual ice-making capacity of a machine is only about one-half of its rated capacity in tons of refrigeration.

125. Coefficient of Performance.—The term "efficiency" as ordinarily applied to machines or engines cannot be applied to a refrigerating system because a refrigerating system does no work in the ordinary sense of the word. The duty of a refrigerating system is the removal of heat, and any expression for the performance of a refrigerating system would be based upon the amount of heat removed. Such an expression may be used in the same sense as the "efficiency" of machines and engines which actually do work. Therefore, in estimating the merit of a refrigerating system we may use the expression

$$\text{Coefficient of Performance} = \frac{\text{Heat extracted from the cold body}}{\text{Work expended}}$$

In applying this expression, both the "heat extracted" and the "work expended" must be expressed in the same units, either B.T.U. or foot-pounds.

The efficiency of a machine or engine can never be more than 1.0 or 100 per cent. because the work obtained from it can never quite equal the energy expended upon it. A refrigerating system on the other hand, may show a coefficient of performance of several hundred per cent., because the heat extracted from the cold body does not depend directly upon the work performed upon the refrigerating substance. The heat is extracted from the cold body (usually the brine) by the evaporation of the refrigerating

agent, and therefore involves the latent heat, which is large in proportion to the amount of refrigerating agent handled.

The mechanical efficiency of a refrigerating machine or compressor may be calculated in the same manner as the mechanical efficiency of an air compressor, that is, by dividing the indicated horse-power of the compressor cylinder by the indicated horse-power of the steam cylinder, or by the power required to run the compressor in case it is run by another source of power than a steam engine.

QUESTIONS

151. How does ice produce a cooling effect?

152. Explain why mixing salt with ice produces a lower temperature than would be produced by the salt alone.

153. At what part of a compression refrigerating system is the refrigeration produced?

154. What is the object in having a compressor in a refrigerating system?

155. Explain the principles upon which an absorption refrigerating system operates.

156. What is the object in having an *exchanger* in an absorption refrigerating system?

157. What substances are used as refrigerating agents in refrigerating systems?

158. Which of these is best? Give the reasons for your answer.

159. Explain the principles upon which a dense air refrigerating system operates.

160. Explain how liquid air is made.

161. 490 lbs. of ammonia are circulated per hour through a compression refrigerating system. The ammonia leaving the compressor has a gage pressure of 128 lb. per sq. in. and a temperature of 85° F. and it enters the condenser at this temperature and pressure. The liquid ammonia leaving the condenser has a temperature of 53° F. and a gage pressure of 128 lb. per sq. in. How many heat units does the ammonia give to the condenser per hour? (Assume the specific heat of gaseous ammonia as .54.)

162. The liquid ammonia reaches the expansion valve in the condition of temperature mentioned above and it leaves the cooler at a gage pressure of 29 lb. per sq. in. How many heat units does the cooler give to the ammonia per hour?

163. The indicated horse-power of the steam engine required to run the above compressor is 18.76. What is the coefficient of performance for the whole system?

CHAPTER XVI

HOUSE HEATING

126. Warming Buildings.—The process of warming buildings is the reverse of that of cooling them, or refrigeration. In refrigeration the inside of the building or compartment is colder than the outside air; consequently there is a leakage of heat from the outside to the inside which must be overcome by the refrigerating system. In house heating the inside of the building is warmer than the outside air, consequently there is a leakage of heat from the inside to the outside and the heating system must supply heat at the same rate it is lost from the building in order to keep it at a uniform temperature. The problem that confronts anyone designing a heating system is, first, to determine the amount of heat that is lost from the building in any given time, as one hour; second, to select the proper type or kind of heating system that is best adapted to heating the particular building under consideration; and third, to proportion the parts of the selected heating system so they will supply heat at the same rate at which it is lost from the building. In doing this the heating apparatus such as the radiators, boilers, etc., must be chosen large enough so they will warm the building to the proper degree during the coldest weather that is likely to be experienced in that particular locality.

127. Loss of Heat from Buildings.—Heat is lost from a building by all three of the methods mentioned in Chapter IV, that is, by radiation, conduction and convection. It would be a long and tedious process to calculate the amount of heat lost from a building in each of these ways, because there are many kinds and sizes of materials in a building and the heat lost from each of these would have to be calculated separately. Such a calculation probably would not be accurate after it was made. For the above reasons heating engineers have adopted a simpler and more direct method of calculating heat loss from buildings.

The total loss of heat from a building is divided into three parts and each calculated separately. These are:- the loss of heat through the walls, the loss of heat by the windows or glass sur-

faces, and the loss of heat by the leakage of cold air into the building and the leakage of warm air out of the building.

The loss of heat through the walls occurs by both radiation and conduction, but in calculations the heat loss by these two methods are combined into one quantity. Many experiments have been made to determine the quantity of heat that will be lost from building walls when there is a constant difference of temperature between the two sides of the walls, such experiments being made on all kinds of construction, material, and thickness of wall, as all of these things affect the loss of heat through them. The results of these experiments are reduced to the number of B.T.U. lost from one square foot of wall surface in one hour when the difference in temperature between the two sides of the wall is one degree, and these values, called "factors of heat loss" are tabulated for convenience in use. Such a table will be found in Chapter IV. More extensive tables than this may be found in various books on heating and ventilating.

With a table of factors of heat loss at hand the process of calculating the amount of heat lost from a building is an easy matter. This is done by multiplying together the number of square feet of outside wall surface, the factor of heat loss, and the difference in temperature between the inside and the outside of the building. Only the outside wall surface, that is, the surface of the wall exposed to the outside temperature, is used, because this is the only wall through which a loss of heat occurs. The temperature on both sides of interior walls is the same; hence there is no loss of heat through them. Since the factors of heat loss are based on one degree difference in temperature on the two sides of the wall, it is necessary, in the above calculation, to multiply by the difference in temperature between the inside and outside of the building.

The above method of calculating the amount of heat lost through a wall may be expressed by the following formula:

$$B.T.U. = fWt$$

in which $B.T.U.$ = the number of B.T.U. lost per hour
f = the factor of heat loss from the tables
t = the difference in temperature between the inside and outside of the building, and
W = the number of sq. ft. of exposed wall surface

Example:

The outside wall of a certain room is 12 ft. long and 9 ft. high. The character of the wall is such that its factor of heat loss is 0.22. A temperature of

70° F. is maintained inside the room. How much heat is lost through the wall if the lowest temperature outside is 0° F.?

Solution:

$W = 12 \times 9 = 108$ sq. ft.
$t = 70 - 0 = 70°$
$f = .22$
$B.T.U. = .22 \times 108 \times 70 = 1663.2$ B.T.U. per hour

The loss of heat through the glass surface, such as windows, skylights, etc., is calculated in the same way as the heat lost through the walls, but a separate calculation must be made for it because the factor of heat loss for glass is different from that for walls. The factor of heat loss for ordinary window surface is 1.0, which is about four times as large as that for an ordinary wall, hence a house having a large number of windows requires more heat to keep it warm than one having only a small glass surface.

The amount of heat lost by leakage of air is the most difficult of all to calculate on account of the variable character of the leakage. Leakage of air occurs through cracks around the windows and doors, by opening doors when people pass in or out, and there is also a certain amount of leakage directly through the walls. It would be impossible to calculate or measure the amount of air leakage from these sources, but it is estimated in practical work to be in one hour a certain number of times the cubic feet of space in the room. For example, the leakage of air is considered to be one times the cubic feet of space in the room per hour for ordinary rooms, 1.5 times for corridors, and 2 to 3 times for vestibules or hallways into which outside doors open. It will be seen that considerable judgment must be used in estimating the leakage of air, such judgment being based upon the construction of the building, whether tight or loose, and upon the number of times the outside doors are opened.

Since 1 B.T.U. will warm 55 cubic feet of air through 1°, the amount of heat lost in one hour through the leakage of air may be calculated approximately by the following formula:

$$B.T.U. = \frac{Cn}{55}t$$

in which $B.T.U.$ = the heat lost per hour due to leakage
C = the cubic contents of the room in cu. ft.
t = the difference in temperature between the inside and outside of the building
n = the number of times per hour the air in the room is changed by leakage

Example:

The living room of a certain residence is 24 ft. long, 14 ft. wide and 9 ft. high, with an outside door opening directly into it. How much heat is lost from this room due to leakage of air when the temperature inside is 70° F. and outside 0° F.? Assume a factor of leakage = 1.75.

Solution:

Cubic contents of room = $24 \times 14 \times 9 = 3024$ cu. ft.

$t = 70° - 0° = 70°$

$n = 1.75$

$$B.T.U. = \frac{Cn}{55} t = \frac{3024 \times 1.75}{55} \times 70 = 6735.2 \text{ B.T.U. per hour}$$

For convenience in making calculations, the heat losses from the three sources mentioned above—walls, windows, and leakage—may be combined into one formula, as follows:

$$H = t\left(\frac{Cn}{55} + fW + G\right)$$

in which G is the number of sq. ft. of surface in the windows, and the other letters have the same meaning as before. In calculating the heat loss from residences, the factor of heat loss from walls is usually taken as .25 or $\frac{1}{4}$.

Example:

What is the heat loss per hour from a room 24 ft. long, 14 ft. wide, and 9 ft. high, one of its long and one of its short walls being outside walls? The short wall has two windows 3 ft. $\times$ 5 ft. and one door $2\frac{1}{2}$ ft. $\times 6\frac{1}{2}$ ft. and the long wall has two windows 3 ft. $\times$ 5 ft. The temperature inside is 70° F. and outside 0° F. Consider the door as losing as much heat as the same amount of glass surface, the number of changes of air as 2, and the factor for the walls 0.25.

Solution:

Cubic contents = $24 \times 14 \times 9 = 3024$ cu. ft.

Glass surface = $4(3 \times 5) + (2\frac{1}{2} \times 6\frac{1}{2})$

$= 60 + 16.25 = 76.25$ sq. ft.

Gross wall surface = $(24 + 14)9 = 342$ sq. ft.

Net wall surface = $342 - 76.25 = 265.75$ sq. ft.

$$H = t\left(\frac{Cn}{55} + fW + G\right)$$

$$= 70\left\{\frac{3024 \times 2}{55} + (.25 \times 265.75) + 76.25\right\}$$

$$= 70(110 + 66.44 + 76.25)$$

$$= 70 \times 252.69 = 17688.3 \text{ B.T.U. per hour}$$

The side of a building that is exposed to cold north winds in the winter times loses more heat than the side which is protected from

the cold winds. For this reason it is customary to add 10 per cent. to the heat loss as calculated by the above method if the room is on the north or west side of a building. Adding 10 per cent. is the same as multiplying 1.1, hence if the room mentioned in the preceding example was on the north side of the building the heat loss from it would be taken as

$$17688.3 \times 1.1 = 19457.1 \text{ B.T.U. per hour.}$$

If a room is on the ground floor and there is an unheated cellar beneath it it is customary to assume that the temperature in the cellar is 32° F. The loss of heat through the floor is then calculated in the same manner as for a wall, using the proper factor of heat loss as found in the tables. It is also customary to calculate the heat loss through the ceiling of a room in the same way where there is an unheated space above. For this purpose a temperature of 32° F. is assumed for an unheated attic.

128. Heat Given off by Radiators.—Practically all radiators, both for steam and for hot water heating, are made of thin cast-iron sections, and a number of sections are joined together to make up the complete radiator. The radiator is placed in the coldest part of a room, usually under a window, and the heat given off from it balances the heat loss from the building, thus maintaining an even temperature in the room. The heat is diffused throughout the room by convection currents in the air which is warmed by coming in contact with the radiator. The air then rises to the ceiling and is diffused throughout the room.

In steam heating the heat is obtained by the condensation of steam in the radiators, the steam thereby giving up its latent heat and maintaining the surface of the radiator at the same temperature as the steam. In hot water heating, a continuous flow of hot water is maintained through the radiator which keeps the surfaces of the radiator at a high temperature. The water is, of course, cooled somewhat in passing through the radiator.

Many tests have been made to determine the amount of heat given off from various kinds of radiators under all sorts of conditions, and, while the results of these experiments vary somewhat, the following table shows approximately the number of heat units given off per hour by each square foot of radiator surface for each degree difference of temperature between the temperature of the radiator surface and the temperature of the room:

Type of radiator	B.T.U. given off per sq. ft. per hour per degree difference of temperature
One-column	1.7
Two-column	1.6
Three-column	1.4
Six-column	1.3
1 in. iron pipe wall coil	2.5

The number of columns in a radiator refers to the width of the radiator and not to the number of sections, or its length. It will be observed that the more columns there are in the width of a radiator the less heat is given off per square foot of surface. This is because a large part of the heat from a radiator is given off by radiation and the interior columns of the radiator interfere with the heat rays radiated from adjacent columns. The most common types of radiators are the two and three column ones.

The amount of radiating surface that must be placed in a room in order to warm it may be calculated by dividing the total heat loss from the room by the amount of heat given off from each square foot of the radiator. The amount of heat given off from each square foot of the radiator may be calculated by the formula

$$H_R = C(t_s - t_r)$$

in which H_R = number of B.T.U. given off from the radiator per sq. ft. per hour

C = Number of B.T.U. given off from the radiator per sq. ft. per hour for each degree difference in temperature between the inside and outside of the radiator as found in the preceding table

t_s = temperature inside the radiator

t_r = temperature of room

Example:

The heat loss from a certain room is 19,457 B.T.U. per hour. How many square feet of cast iron two-column radiator must be installed in this room to maintain it at 70° F.? The steam pressure in the radiator is 2.3 lb. per sq. in. gage or 17 lb. per sq. in. absolute.

Solution:

The temperature of steam at 17 lb. pressure is (from the steam table) 219.4° F.

The factor of heat loss from a two-column radiator is (from the preceding

table) 1.6 B.T.U. per hour per degree. The temperature of the room is 70°. The amount of heat given off by one square foot of radiator is

$$\begin{aligned} H_R &= C(t_s - t_r) \\ &= 1.6(219.4 - 70) \\ &= 1.6 \times 149.4 \\ &= 239 \text{ B.T.U.} \end{aligned}$$

Number of square feet of radiator surface required in the room is

$$\frac{19457}{239} = 80.5 \text{ sq. ft.}$$

The total amount of heat given off by a radiator is found by multiplying together the heat given off per square foot of surface and the total number of square feet of surface.

129. Systems of Heating.—Modern systems of heating buildings may be divided into two general classes called respectively *direct* systems and *indirect* systems. A direct system of heating is one in which the source of heat, such as the radiators, are placed directly in the room to be warmed. In this class are included the ordinary steam and hot water systems and also various so-called vacuum systems of heating. An indirect system is one in which the source of heat is located outside the room. In this system the heating is done by means of warm air which is heated outside the rooms and then brought in through suitable pipes. In this class are included the ordinary warm air furnace, fan systems in which the warm air is circulated by means of a fan, and also steam and hot water indirect heating, but the last two systems are not in common use.

130. Steam Systems.—A direct system of steam heating consists of a boiler, usually located in the basement, and radiators placed in the rooms. The radiators are connected to the boiler by pipes which carry the steam. The simplest arrangement of piping for this kind of heating plant is known as the single-pipe system, illustrated in Fig. 105. In this system of piping only a single pipe is used to carry the steam from the boiler to the radiator and return the water resulting from the condensation of steam (spoken of as the condensation) from the radiator to the boiler. The pipes must have a pitch or slope downward toward the boiler so the water may drain back by gravity. There is no difficulty about draining the water through the vertical pipes, or risers, but it is very important to give the mains or pipes in the basement sufficient slope in the proper direction. These pipes are usually pitched at least one inch in ten feet of length. The

water and steam flow in opposite directions through the same pipe in this system; hence the pipes must be large enough to prevent any interference between the water and steam.

In the two-pipe system of steam heating illustrated in Fig. 106, there is one pipe for carrying the steam to the radiators and another for returning the condensation. The pipes carrying steam are connected to the top of the boiler and the return pipes are connected near the bottom below the level of the water in the boiler. The main steam and main return pipes in the basement are connected at their ends and the main steam pipe is pitched

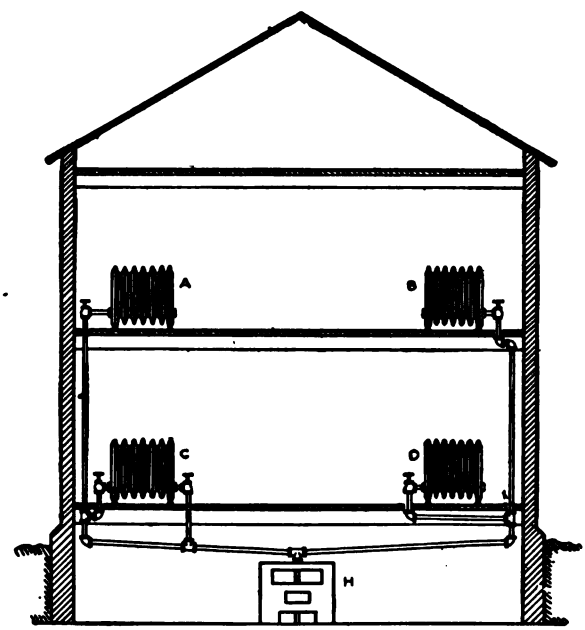

FIG. 105.

downward away from the boiler in order to drain the small amount of condensation that collects in it into the return pipe.

Very little water flows through the steam pipe in the two-pipe system and this flows in the same direction as the steam, hence the pipes may be of smaller size. On the other hand, there are more pipes in the two-pipe system, hence this system costs more to install than the single-pipe system. There is a more positive circulation of steam in the two-pipe system which causes the

radiators to receive the heat more quickly, and there is also an absence of noise due to water-hammer, which is sometimes annoying with the single-pipe system.

Another system of piping commonly used in steam heating is known as the combination system. This consists of a combination of the one and two-pipe systems. The vertical pipes or risers supplying the radiators are single pipes as in the ordinary single-pipe system, and the mains in the basement are on the two-pipe system with separate steam and return pipes. This

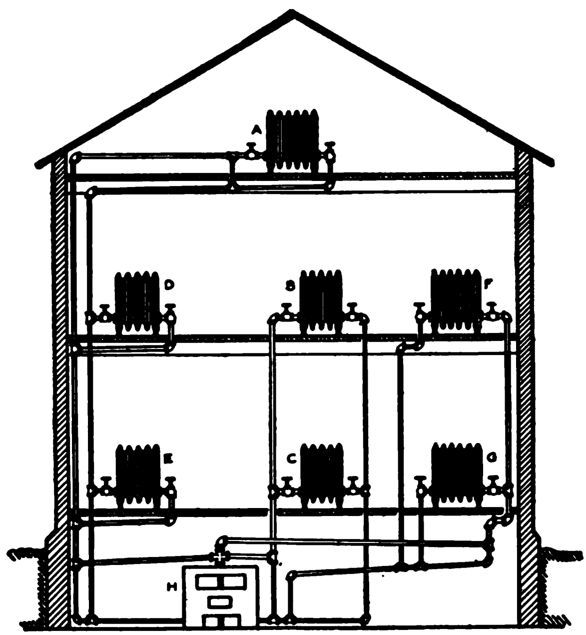

FIG. 106.

system combines most of the advantages of the two-pipe system but does not cost as much.

In the indirect system of steam heating the radiators are placed in galvanized sheet-iron boxes located under the floor and near the point at which the warm air is to be discharged into the room, as illustrated in Fig. 107. The galvanized iron box fits up close against the sides of the radiator so that no air can pass it without coming in contact with the heating surfaces. A space of about 10 inches is left between the radiator and the top and bottom of

the box. Cold air is brought from out-doors to the bottom of the box through a galvanized iron duct. This air then passes up through the radiator and is warmed by contact with its hot surfaces. It then passes up to the room above through a galvanized

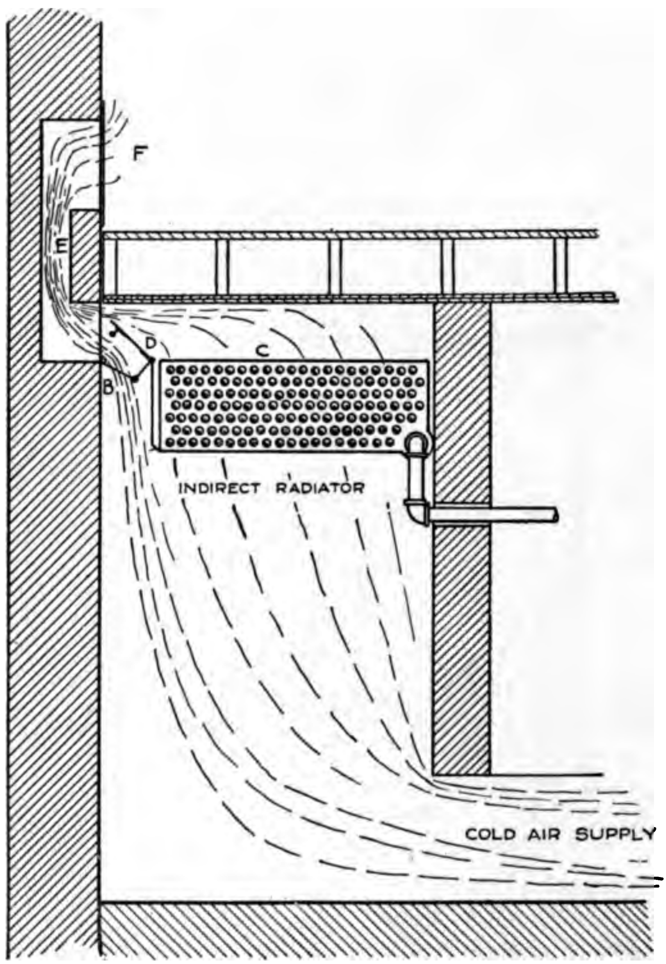

Fig. 107.

iron duct, which opens from the top of the radiator box, and is discharged into the room through a register placed in the wall. After passing through the radiator the air has a temperature of 120° to 140° F.

Regulation of the temperature is secured by carrying some cold air around the radiator through a by-pass, as shown, and mixing this cold air with the warm air leaving the radiator. A mixture having the desired temperature is secured by means of an adjustable mixing damper controlled from the room above.

In indirect heating, a room is heated by the cooling of the warm air. If the temperature of the room is maintained at 70° F., the warm air can only cool to this temperature in giving up heat to the room. If the outside air has a temperature of 0° F. and its temperature is 130° F. when it enters the room, then it can lose only $130° - 70° = 60°$ in heating the room, although the air itself has been heated from 0° F. to 130° F. It is thus seen that only about one-half of the heat given to the air is available for heating the room. For this reason the indirect system is not nearly as efficient as the direct and it is not used to so great an extent. It has the distinct advantage, however, that it ventilates the rooms that it heats by bringing in fresh air, whereas the direct system does not.

On account of the cold air coming in contact with the radiator surface in the indirect system these surfaces condense much more steam per square foot of surface than do direct radiators. In order to take care of the large amount of water resulting from this condensation, indirect radiators are always connected on the two-pipe system. If they were connected on the single-pipe system the condensation leaving the radiators would interfere with the steam entering them and this would cause a disagreeable rattling and pounding noise in the radiators.

131. Hot Water Heating.—Hot water heating is made possible by the fact that when water is heated it tends to rise. A hot water heating system, as shown in Fig. 108, resembles in appearance a two-pipe direct system of steam heating, except that it is not necessary to connect the ends of the main pipes in the basement, and the main pipes are pitched upward instead of downward. One of the pipes, called the *flow pipe*, carries the hot water to the radiators and the other, called the *return*, brings the cooler water back to the boiler to be heated again. The flow pipe is connected to the top and the return is connected to the bottom of the boiler, all of the pipes, radiators, and boiler being completely filled with water. When the water is heated it rises to the top of the boiler and passes out through the flow pipe to the radiators, thus forcing the cooler water to return to the boiler through the return pipes.

Since water expands when it is heated it is necessary to provide for expansion in a hot water heating system; otherwise, the system being entirely filled with water, some part of it would burst when the water was heated. Expansion is provided for by placing an expansion tank at the top of the system of piping. The expansion tank is open to the atmosphere. The system is

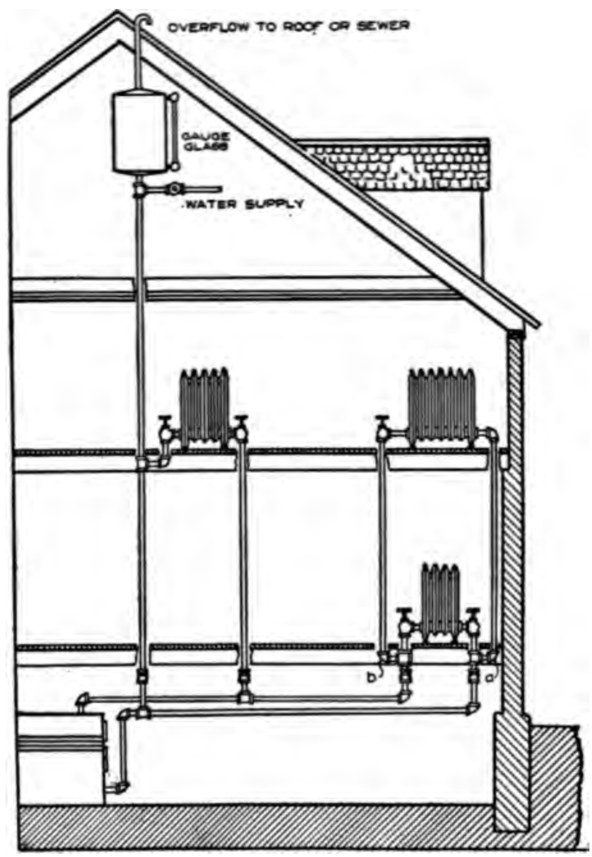

FIG. 108.

filled with water up to the bottom of the expansion tank; then, when the water is heated and expands, it rises into the expansion tank to accommodate its increased volume.

Hot water heating systems are usually designed to properly heat a building with a maximum temperature of the water of about 180° F. The water will then be cooled to about 160° F. in

passing through the radiator. This gives an average temperature of the radiator surfaces of about 170° F. which is much lower than the temperature of steam radiators and therefore requires considerably larger radiating surface with a hot water system than with a steam system. On account of the larger radiators and pipes required with a hot water system this system costs more to install than does a steam system. On the other hand, the lower temperature employed gives a more pleasing sensation of warmth than does the hotter steam radiator.

Indirect heating is sometimes done with hot water radiators but has not proved very popular because of the danger of the radiators freezing and bursting during cold nights.

132. Warm-air Furnace.—Heating by means of a warm-air furnace is a development of the method of heating houses by means of stoves. The warm-air furnace resembles a large stove surrounded by a sheet iron casing with a space for the passage of air between the casing and the stove. A warm-air furnace is illustrated in Fig. 109, which shows its resemblance to a stove, the casing and outlets being indicated by the dotted lines. In operation, fresh air is taken from out-doors and carried through a large pipe to a pit underneath the furnace. From here it passes up through the space between the furnace and casing and is warmed by contact with the fire pot, combustion chamber, and radiator. It then passes out the top of the casing and is carried to the rooms above through tin pipes of suitable size. The radiator placed above the fire pot is simply a hollow chamber through which the hot gases from the fire pass on their way to the chimney, and is intended to expose more hot surface for heating the air. The fire pot, combustion chamber, and radiator are usually made of cast iron as this metal stands the intense heat from the fire without injury.

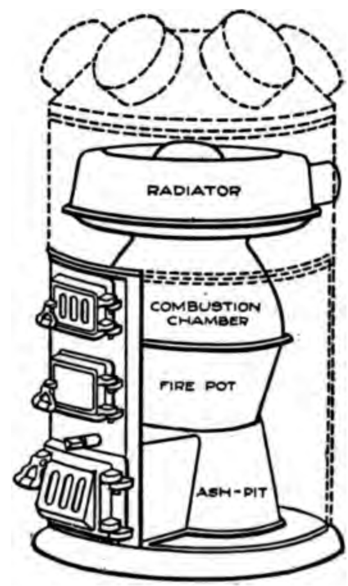

FIG. 109.

The circulation of air through the furnace and pipes is caused by heating the air, which expands it, makes it lighter, and causes it to rise. More cold air then comes in to take the place of the warm air. There is thus produced a continual flow of air from out-doors to the furnace and then to the rooms to be heated. The force moving the air through a furnace is very feeble; hence the circulation of air is easily affected by unfavorable conditions. For this reason, rooms located on the side of a house which is exposed to cold winds are sometimes difficult to heat.

In designing furnace systems of heating it is estimated that the temperature of the warm air entering the rooms will be about 140° F. It may then cool to 70° in giving up heat to the room, that is, about one half of the heat given to the air is available for heating the room. In this respect the furnace system is like the indirect steam or hot water systems, and, like them, is not as efficient as the direct steam or hot water systems.

The pipes carrying the warm air from the furnace to the rooms must be made large enough to deliver the required amount of heat to the rooms. A velocity of air in the pipes of 4 ft. per second may be assumed for pipes leading to the first floor, 5 ft. per sec. for pipes leading to the second floor, and 6 ft. per sec. for pipes leading to the third floor.

The amount of heat required to warm one cubic foot of air is

$$H = t \times .066 \times .242 = .01597t$$

In the above formula t is the range of temperature through which the air is heated, .066 is the weight of one cubic foot of air at 140° F., and .242 is the specific heat of air.

If outside air enters the furnace at 0° F. and is heated to 140° F., it carries into the room

$$H = (140-0).01597 = 2.24 \text{ B.T.U. per cu. ft.}$$

Of this heat only $\frac{70}{140}$ is available for supplying the heat loss from the room, or $\frac{70}{140} \times 2.24 = 1.12$ B.T.U. per cu. ft. Suppose the heat loss from the room is 16,000 B.T.U. per hour, then the amount of warm air that must enter the room is

$$\frac{16{,}000}{1.12} = 14{,}286 \text{ cu. ft. per hour}$$

or

$$\frac{14{,}286}{3600} = 3.77 \text{ cu. ft. per second}$$

If the room to be heated is located on the second floor the area of the pipe leading to it must be

$$\frac{3.77}{5}=.754 \text{ sq. ft.}$$

The area of the pipe supplying cold air to the furnace is made about 80 per cent. of the combined areas of all the warm-air pipes.

133. Fan System of Heating.—The fan system of heating is an indirect system in which the heated air is forced through the ducts and into the rooms by means of a fan. Other indirect systems of heating, such as the warm-air furnace and the indirect steam system, have the objection that the currents of air are very feeble and are easily affected by outside influences such as strong

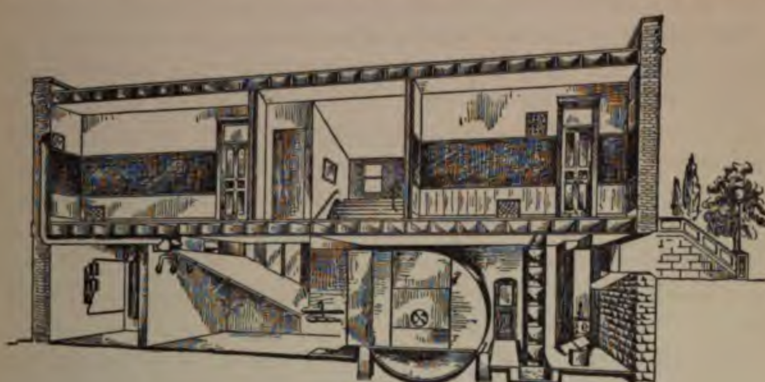

Fig. 110.

winds and friction in the ducts. These objections are overcome in the fan system by forcing the air into the rooms under a slight pressure.

The fan system consists of a fan driven by a steam engine or electric motor, a number of coils of steam pipe through which the air is blown in order to warm it, and a system of ducts or pipes for distributing the warm air to the rooms. The arrangement of this apparatus is illustrated in Fig. 110, which shows the steam coils divided into two parts. One part of the coils pre-heats the air to about 70° F. before it reaches the fan, and the other part heats the air from 70° to about 140°, at which temperature it enters the rooms. Some of the pre-heated air is by-passed around the second set of steam coils and is later mixed with the warmer

air through an adjustable damper in order to regulate the temperature in the room.

There are various modifications of the fan system of heating as outlined above. In some cases the air is drawn through the heater coils by the fan instead of being blown through. In some systems the heated air is forced directly into the ducts while in others the air is blown into a small room called a plenum chamber, from which the various ducts leading to the rooms are taken. In still other systems only enough air is blown into the rooms to ventilate them, the air having a temperature of about 70° F., and the heat loss from the rooms is supplied by direct steam radiators placed in the rooms.

The fan system of heating is subject to the same fault as other indirect systems, that is, if the heating is done entirely by warm air, only about one-half of the heat put into the air is available for heating, the other half being lost in the air that leaks at room temperature from the building. On the other hand, it is the only system suitable for heating and ventilating large buildings where the ducts must be long and tortuous. With this system it is also possible to wash and moisten the air by passing it through a spray of water located between the first steam coils and the fan. This is often done in large cities where the air contains dust and soot and also in school buildings in order to make the air more humid and pleasanter to breathe.

The type of fan most often used to move the air in the fan system of heating is known as a steel plate fan. It consists of radial blades fastened to a spider or hub which, in turn, is fastened to the shaft. The blades are enclosed in a case or housing made of sheet steel. Air enters the fan at the center and is discharged at the periphery, the pressure generated being from $\frac{1}{4}$ to 1 oz. per sq. in. depending upon the friction to be overcome.

The steam coils are made from 1-in. pipe placed about $2\frac{1}{2}$ inches from center to center, the coils being of rectangular shape with both ends of the pipe connected to a hollow iron base. The base is divided into two compartments, one for steam and one for the condensation. One end of each coil is connected with the steam compartment and the other end with the condensation compartment.

The ducts are usually made of galvanized sheet iron and are proportioned so that the velocity of the air through them will be from 600 to 1500 feet per minute.

If the fan is run by a steam engine, the exhaust steam is used to supply part of the heater coils, the balance of the steam required being taken from the boiler at reduced pressure. By this arrangement the heat contained in the exhaust steam is saved, and it adds considerably to the efficiency of the heating system.

QUESTIONS

164. What are the sources of heat loss from a house?

165. How is the size of a radiator to heat a room determined?

166. Why is a three-column radiator not as efficient as a two-column one?

167. How does an indirect system of heating compare in efficiency with a direct system?

168. In a steam-heating system how is heat transferred from the steam to the room to be heated?

169. Why should hot water pipes pitch upward?

170. Why is an expansion tank placed on a hot water heating system?

171. A room 30 ft. × 16 ft. with a 9 ft. ceiling has one of its long and one of its short sides exposed, the long side being toward the north. The short side contains 3 windows and the long side 4 windows, each 2½ ft. × 6 ft. The room is of frame construction with lath and plaster on the inside and ¾ inches sheating, clapboards, and paper on the outside. The inside of the room is to be maintained at 70° F. and the coldest outside temperature is 20° F. below zero. How many square feet of direct steam radiation should be placed in this room? Steam pressure 2 pounds gage. Use 2-column radiators.

172. How many square feet of 2-column hot water radiators should be placed in the above room?

173. If this room is on the first floor and is to be heated by a warm air furnace, what should be the size of the air pipe leading to it?

INDEX

Figures refer to pages.